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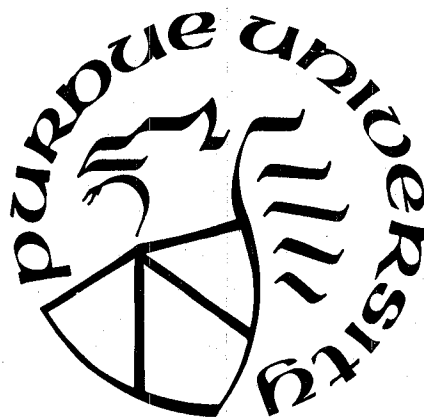
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THE INTEGRATED
MANUAL AND AUTOMATIC CONTROL
OF COMPLEX FLIGHT SYSTEMS

Semi-Annual Status Report
for the Period July 1, 1983 - Jan. 31, 1984

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N84-18207 #

1. Introduction

This constitutes the semi-annual status report for the period July 1, 1983 - Jan. 31, 1984 on the research being performed by the School of Aeronautics and Astronautics, Purdue University, for the NASA Dryden Flight Research Facility, Ames Research Center, under Grant NAG4-1. The objectives of this research effort have been the development of a unified control synthesis methodology for complex and/or non-conventional flight vehicles; to understand, enhance, and develop prediction techniques for the handling characteristics of such vehicles; and to address pilot parameter identification from experimental data.

2. Technical Comments

The development of a closed-loop methodology for the landing task has been actively pursued during this reporting period. The approach centers on application of an optimal-control "pilot model" for evaluating the closed loop pilot-vehicle system in terms of its time - and frequency-domain characteristics. The intent is to model the closed-loop system so as to approximate as well as possible the important system dynamics appropriate to the landing task, and then identify salient model-based parameters that correlate strongly with the pilot's subjective evaluations, so as to expose poor aircraft dynamics for the task.

We may conceptually represent the task as shown in Figure 1, where the selection of the reference variable Y_c , and the response variable Y is an integral part of the modeling procedure. In the flare and landing one might select Y_c to be altitude, or h_c , and the output of interest of course is then h . In contrast, one might argue that the reference variable of interest is γ_c (or \dot{h}_c) with h_c ignored. So the sketch in

A CANDIDATE MODEL FOR THE LANDING TASK

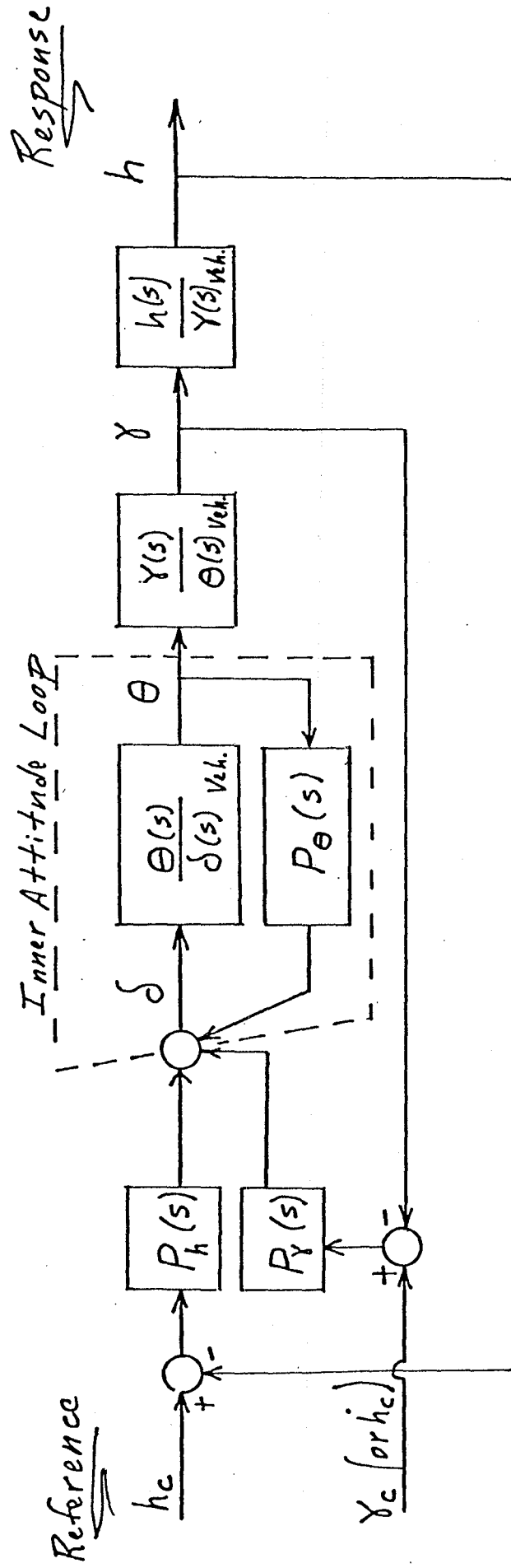


Figure 1, Conceptual Block
Diagram

Figure 1 is intended to be somewhat general, and both cases may be modeled.

In any case we see the inner (dashed box) loop of pilot-compensated attitude dynamics is imbedded in this structure. (This loop was of course the only loop being considered when analyzing the attitude tracking task.) Then the appropriate outer loop structure reflects the flight path and/or altitude regulation components of the landing task. It is significant here that via the optimal control model (OCM), all three pilot "transfer functions" P_θ , P_γ , and P_h are analytically determined, and the block diagram of Fig. 1 may be represented in a variety of forms using block diagram algebra. The frequency-domain characterization of this system is in any case obtainable from this modeling result.

The analysis procedure then involves determining if correlation exists between PIO and Cooper-Harper ratings and pilot comments from flight, and the analytically derived closed-loop system bandwidth, pilot phase compensation, and overall "loop quality" (e.g. stability robustness) obtained from the above modeling approach. A preliminary analysis of some LAHOS (Ref. 1) data will be presented here. The "raw" results from the modeling is tabulated in the Appendix to this report.

We will focus here on the task modeled as flight-path (or sink rate) control, so in terms of the sketch in Fig. 1, h_c is ignored and the "closed-loop" system of interest is γ/γ_c . The task is defined in terms of the OCM cost function as choosing the necessary "control law" to minimize γ tracking error, or

$$J_p = E\left\{\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T [(\gamma - \gamma_c)^2 + r \dot{\delta}_{st}^2] dt\right\}$$

The single control input considered is the stick (elevator).

After modeling the selected configuration with the OCM. The block diagram results from Figure 1 may be expressed, if desired, as shown below in Fig. 2.

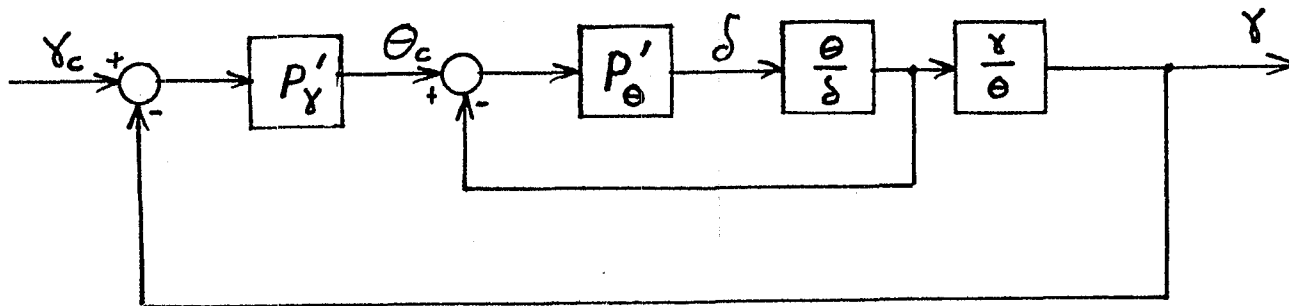


Fig. 2. Intermediate Form

(That is P'_γ and P'_θ in Figure 2 is determined from P_γ , P_θ , θ/δ , γ/θ , etc. from Fig. 1.) Now, since the γ/γ_c dynamics is of interest here (rather than θ/θ_c in attitude tracking), we represent the system in final form as shown in Figure 3.

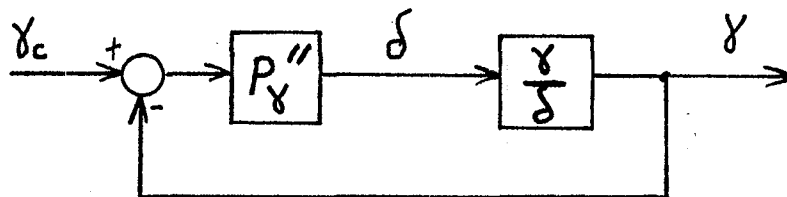


Fig. 3. Final Form

Now the hypothesis is that the pilot's rating of the aircraft in the landing task is determined by the "quality" of the closed loop system and the workload necessary to achieve that "quality". The most important

measure of quality here is stability robustness, evaluated in terms of open-loop (Bode) frequency characteristics. The measure of workload is taken as phase lead necessary to achieve this stability.

Shown in (the solid curve in) Figure 4 is the Frequency Response of the Pilot describing function P_Y'' (from Figure 3) for LAHOS Configuration 2-1. Shown in Figure 5 are the open and closed-loop frequency response (i.e. γ loop opened and closed in Fig. 2) for this case. We define the bandwidth of interest here as the frequency at which open-loop phase is -180° , since this reflects a critical point regarding stability.

We will take as a measure of loop quality, for example, the open-loop magnitude peak (near $\omega = 6$ rad/sec in Fig. 5). We will take as a measure of workload, the pilot phase angle at the open-loop phase bandwidth defined above.

These data, along with open-loop (phase) bandwidth and pilot rating are shown in Table 1.

Note from this data the strong correlation between rating and pilot phase compensation required to achieve a stable system. Furthermore, excessive lag (config. 5-1) is undesirable. Also note for configurations with nearly equal pilot phase (e.g. configs 1-1, 2-3, 3-1, 3-2), the ratings show correlation with open-loop frequency response "peak" (selected as a crude measure of loop quality).

We are encouraged by such results, and will continue evaluating more configurations from the LAHOS data base.

3. Reference

Smith, R.E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities," AFFDL-TR-78-122, Vols I and II, March, 1978.

Table 1
Preliminary Results

Config. [†]	P.O.R.	Bandwidth*	Pilot Phase**	Peak***
1-1	4	3.2 (rad/sec)	75 (deg)	-1. (db)
2-1	2	3.3	45	-1.
2-2	4, 4.5	3.2	59	3.5
2-3	6	3.0	75	5.6
3-1	4, 5, 7	3.4	66	-1.5
3-2	7	3.2	78	2.3
3-3	10	3.1	96	3.5
4-1	2	3.3	38	-1.
5-1	5, 7	3.3	-5	-0.5

*Frequency at which Open-loop Phase = -180°

**Phase Angle of Pilot (δ/ϵ_Y) Describing Function Near Bandwidth Frequency

***Peak of Open-Loop Magnitude Above Bandwidth Frequency

[†]For a description of the Configuration, See the Appendix

APPENDIX

Appendix

Modeling Data

Description of Flight Configurations (from Lahos report)

1-1 Short period: $\lambda = -.75 \pm .695j$
 $\xi = .735$ $\omega_0 = 1.025$ rad/sec.

Phugoid $\lambda = -.022 \pm .13j$
 $\xi = .166$ $\omega_0 = .132$ rad/sec.

No control system dynamics

Overall pilot rating = 4

Slight tendency to PIO near ground.

2-1 Short period: $\xi = .57$
 $\omega_0 = 2.3$ rad/sec.

Phugoid $\xi = .1483$
 $\omega_0 = .17$

No control system dynamics

Overall pilot rating = 2

3-1 Short period: $\xi = .25$
 $\omega_0 = 2.2$ rad/sec

Phugoid $\xi = .1346$
 $\omega_0 = .195$ rad/sec

No control system

Pilot rating overall = 4, 7, 5

Bobbled in turbulence

No PIO on landing

Approach most difficult.

4-1 Short period $\xi = 1.06$
 2 real roots $\lambda = -1.39, -2.84$
 Phugoid $\xi = .249$
 $\omega_0 = .1175$

No control system

Pilot rating overall = 2

5-1 Short period $\xi = .535$
 $\omega_0 = 3.885$
 Phugoid $\xi = .150$
 $\omega_0 = .1799$

No control system

Pilot rating overall = 5, 7

PIO in FLARE and touch down

Touchy airplane

2-2 Same aircraft dynamics as 2-1
 with a $(\frac{1}{.1s+1})$ in the pilots control path
 as a control system.

Pilot rating overall = 4, 4½

Slight overcontrol in landing

2-3 Same A/C as in 2-1
 with a $(\frac{1}{.25s+1})$ in the pilots control path.

Pilot rating overall = 6

PIO in FLARE

3-2 Same A/C dynamics as 3-1

with a $(\frac{1}{.1s+1})$ in the control path as a control system.

Overall pilot rating = 7

PIO in FLARE - tendency to overcontrol

3-3 A/C dynamics of 3-1

Control system $(\frac{1}{.25s+1})$

Overall pilot rating = 10

Tendency to PIO - work hard.

This contains a summary of the (9) Flight Configurations out of Lahos that have been looked at so far.

There is:

- ① Tables of bandwidth, pilot compensation sensitivities for pitch attitude, flight path and altitude tracking.
- ② Scatter plots that cross plot the data in the tables.
- ③ Frequency response plots of loop closures and individual elements from pirep for each of these cases.

PITCH ATTITUDE TRACKING

CONFIGURATION	BANDWIDTH	PILOT RATINGS
1-1	3.026 RAD/SEC	4
2-1	3.358	2
3-1	3.295	5.5
2-2	3.070	4
2-3	2.897	6
3-2	3.024	7
3-3	2.875	10
4-1	3.343	2
5-1	3.735 RAD/SEC	6

CONFIGURATION	SENSITIVITY (db)	SENSITIVITY (ABS)	PILOT RATINGS
1-1	.906	1.425	4.
2-1	1.757	2.851	2
2-2	1.797	3.157	4
2-3	1.595	2.965	6
3-1	.303	.594	5.5
3-2	1.605	3.626	7
3-3	.760	1.896	10
4-1	1.610	2.417	2
5-1	2.164	3.211	6

PITCH ATTITUDE TRACKING

CONFIGURATION	PILOT COMP. AT BANDWITH	ADJUSTED PILOT COMP. AT BANDTH.	PILOT RATING
1-1	16.741 (deg.)	68.248	4
2-1	-12.911	44.128	2
2-2	- 1.825	50.414	4
2-3	11.774	61.131	6
3-1	5.477	61.467	5.5
3-2	16.415	67.895	7
3-3	29.327	78.318	10
4-1	-17.602	39.191	2
5-1	-46.714	16.560	6

CONFIGURATION	RESONANT PEAK	PILOT RATING
1-1	3.949	4
2-1	4.039	2
2-2	4.720	4
2-3	5.251	6
3-1	5.988	5.5
3-2	6.947	7
3-3	7.983	10
4-1	3.396	2
5-1	3.173	6

PITCH ATTITUDE TRACKING

CONFIGURATION	(SENSITIVITY db)*(droop)
1-1	.462
2-1	1.7165
2-2	2.094
2-3	2.061
3-1	.3829
3-2	2.433
3-3	1.311
4-1	.807
5-1	2.415

Some Definitions of Things on the Scatter Plots

Peak sensitivity*droop: This is the sensitivity of the maximum resonant peak to a change in forward loop gain times the low frequency droop. It used the peak sensitivity defined as sensitivity (db) below.

Resonant peak sensitivity (db): This is a sensitivity done leaving everything in db.

$$\text{sensitivity (db)} = \frac{\text{PEAK2} - \text{PEAK}}{20 \log_{10} (1.05)}$$

PEAK2 is new closed loop resonant peak with forward loop gain increased by $20 \log (1.05) = .42\text{ db}$.

PEAK is the old (original) resonant peak.

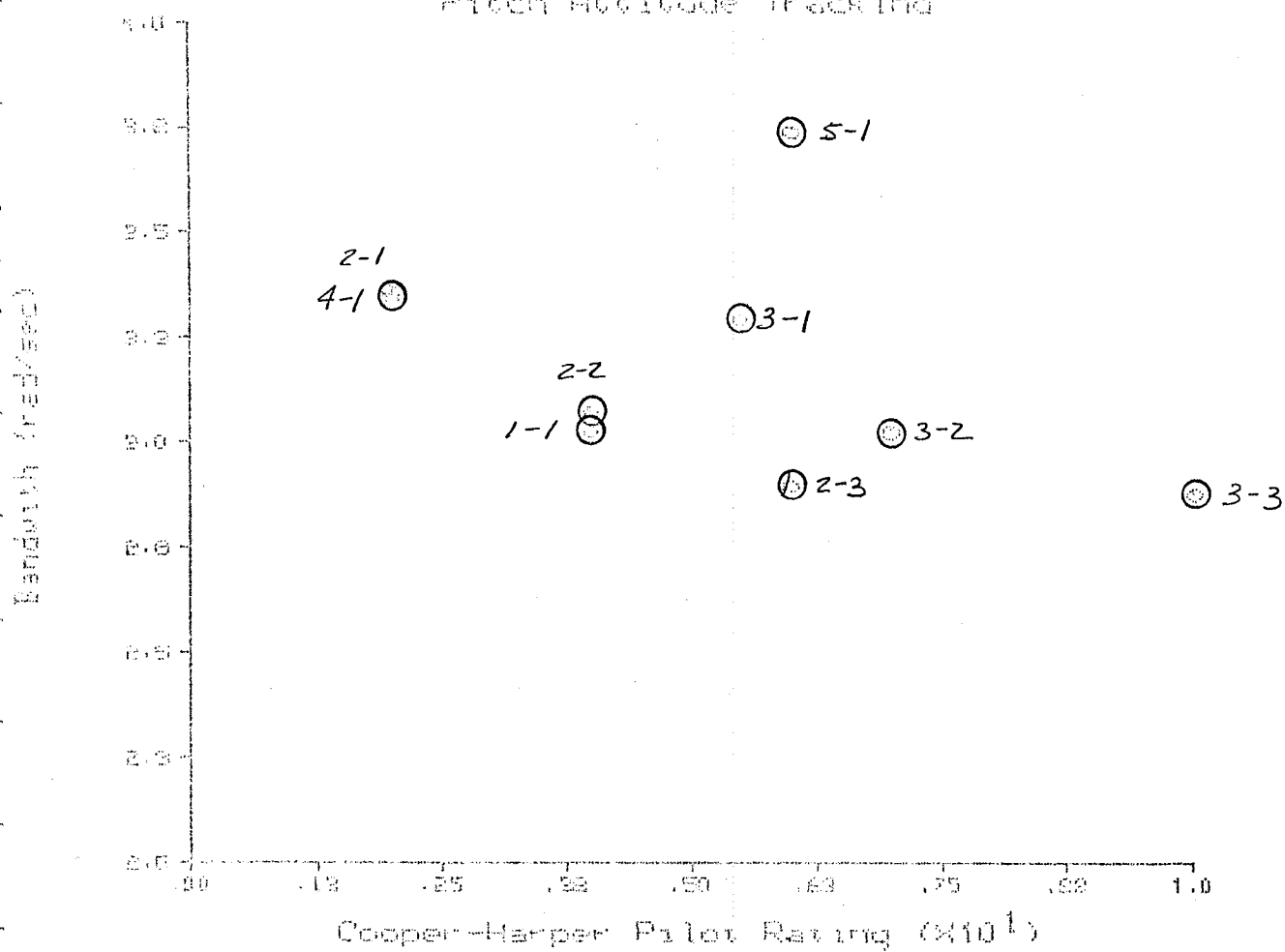
Resonant Peak Sensitivity (abs): Same as above using absolute (not db) units.

$$\text{sensitivity (abs)} = \frac{10^{(\text{PEAK2}/20)} - 10^{(\text{PEAK}/20)}}{.05}$$

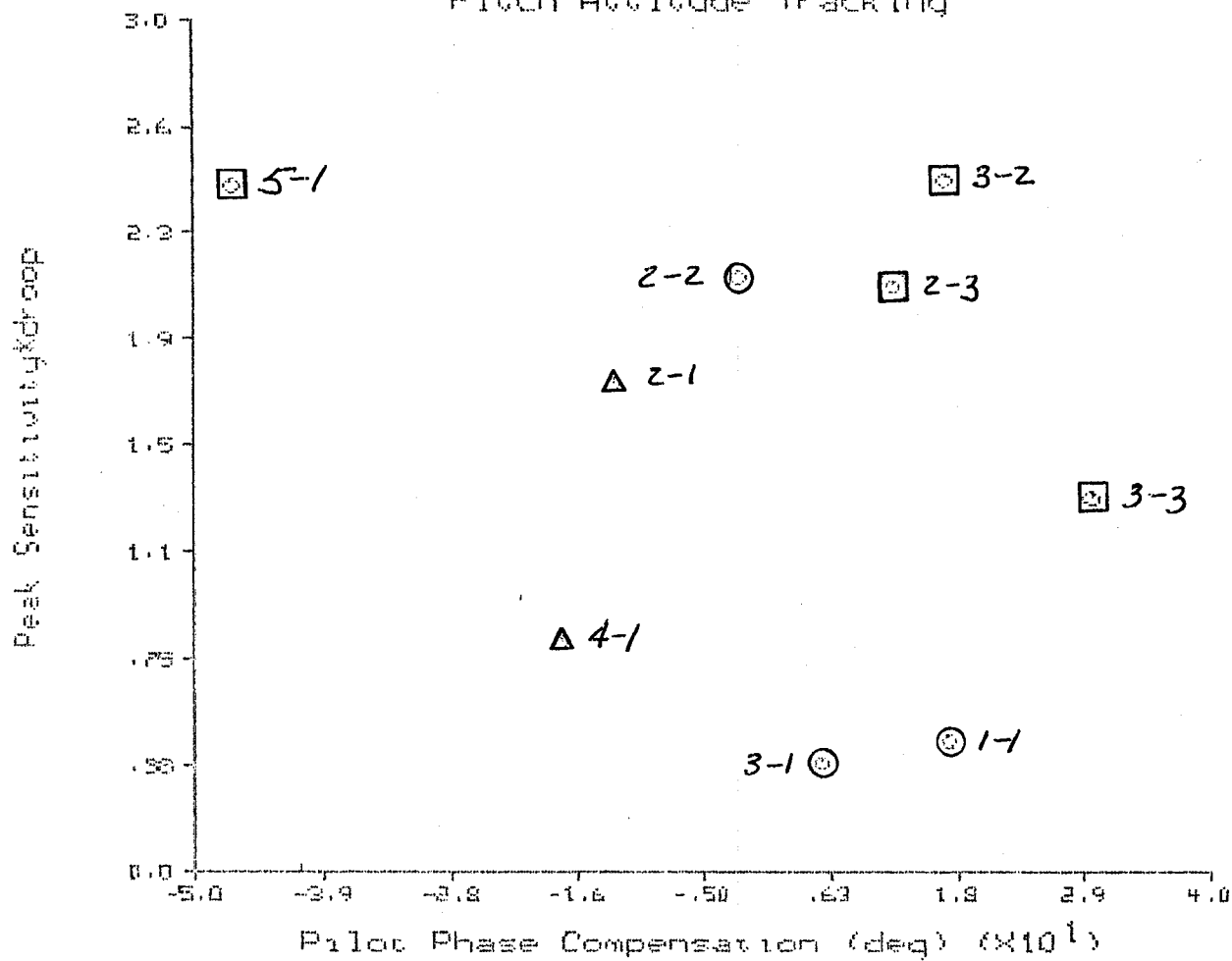
Legend for Plots

△	LEVEL I	AIRPLANE
○	LEVEL II	AIRPLANE
□	LEVEL III	AIRPLANE

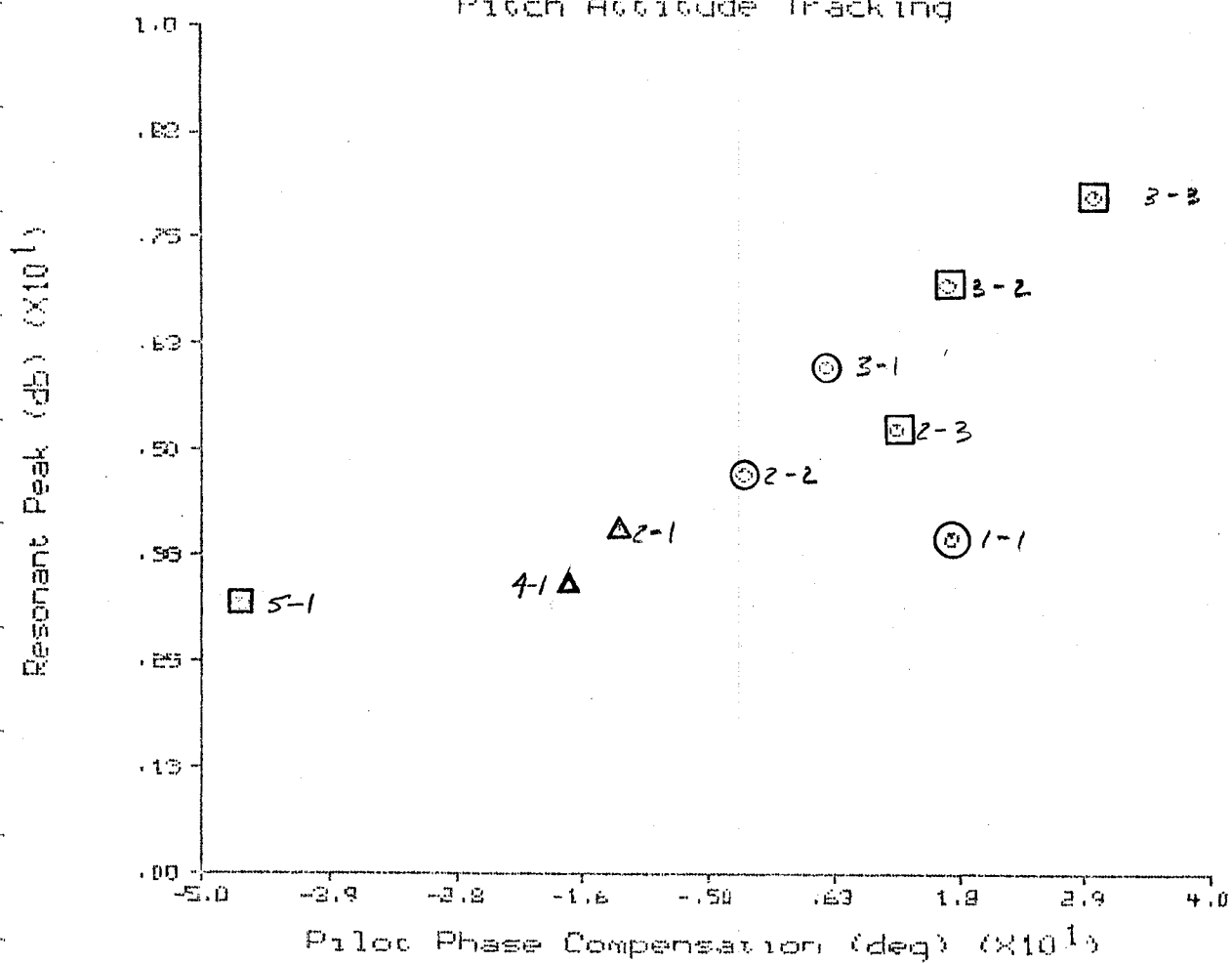
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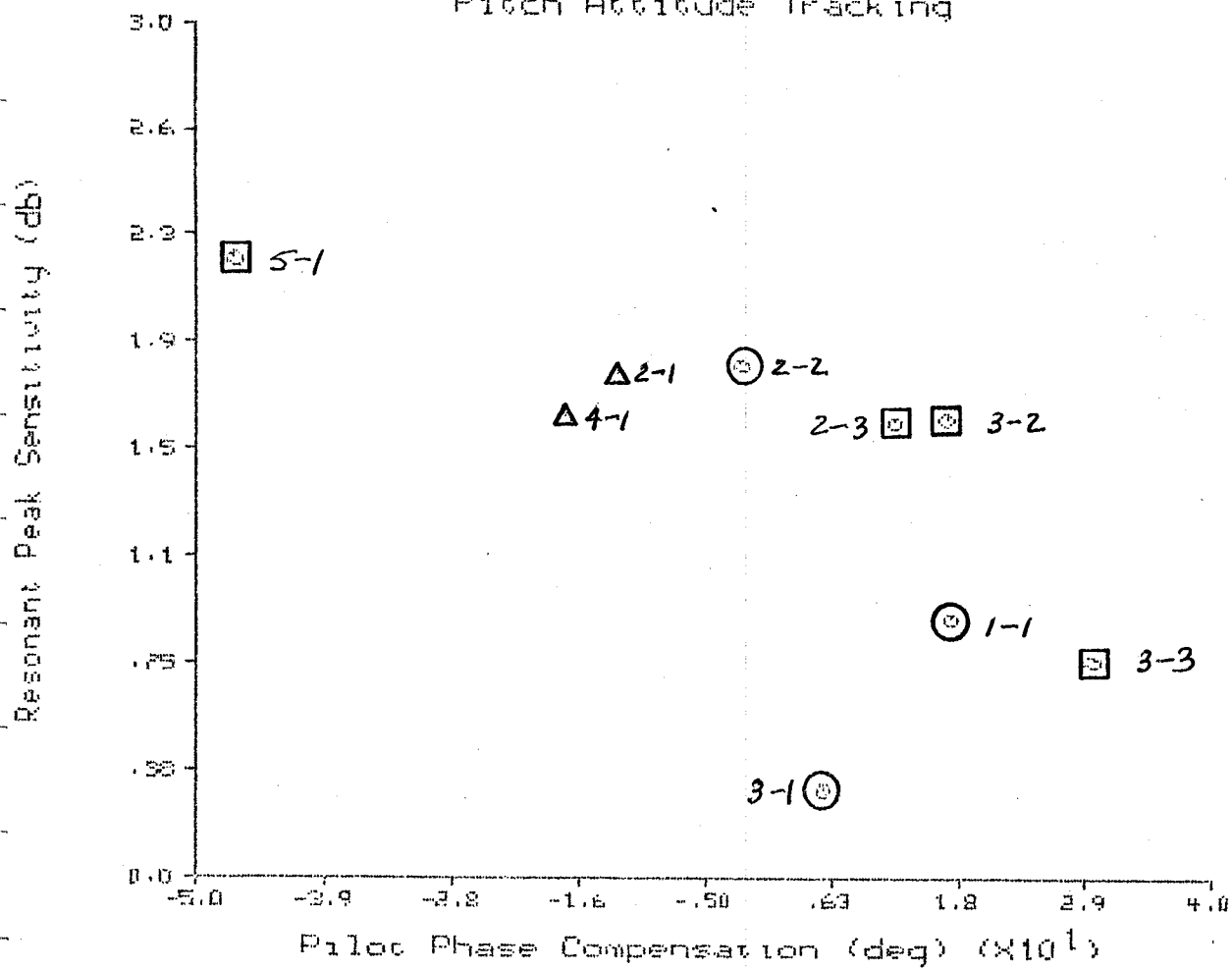
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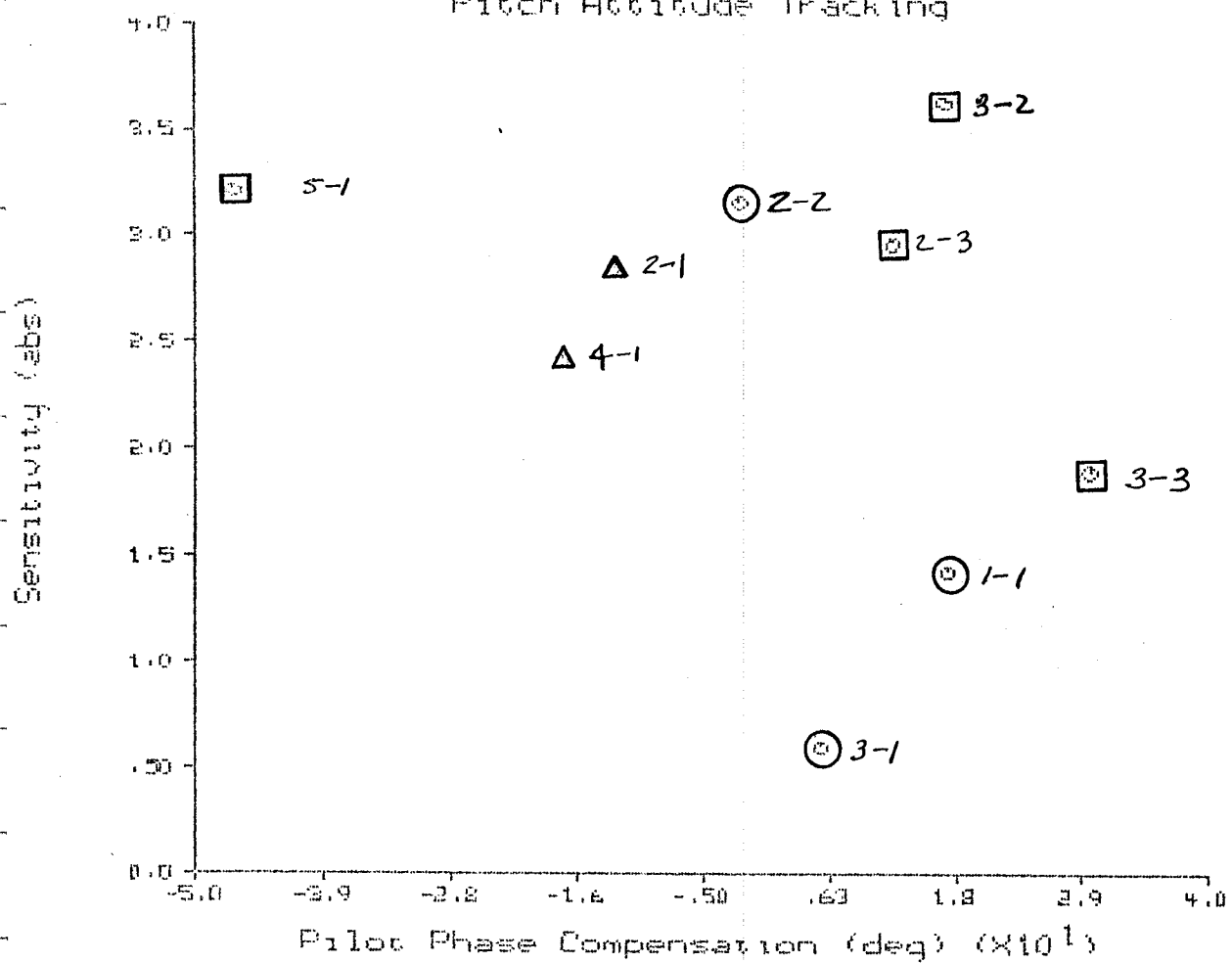
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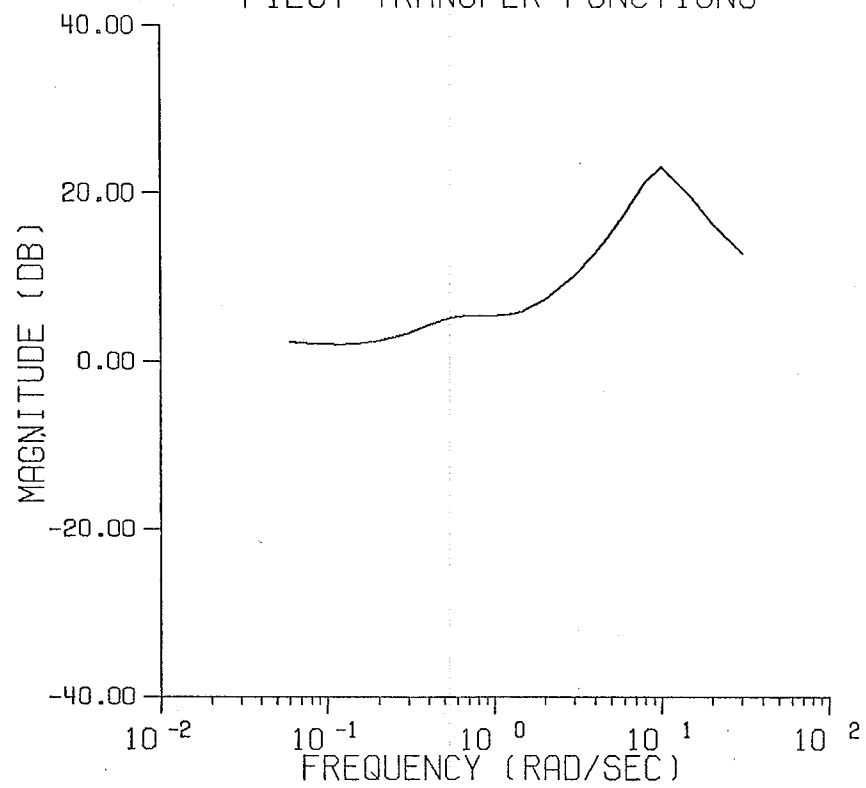
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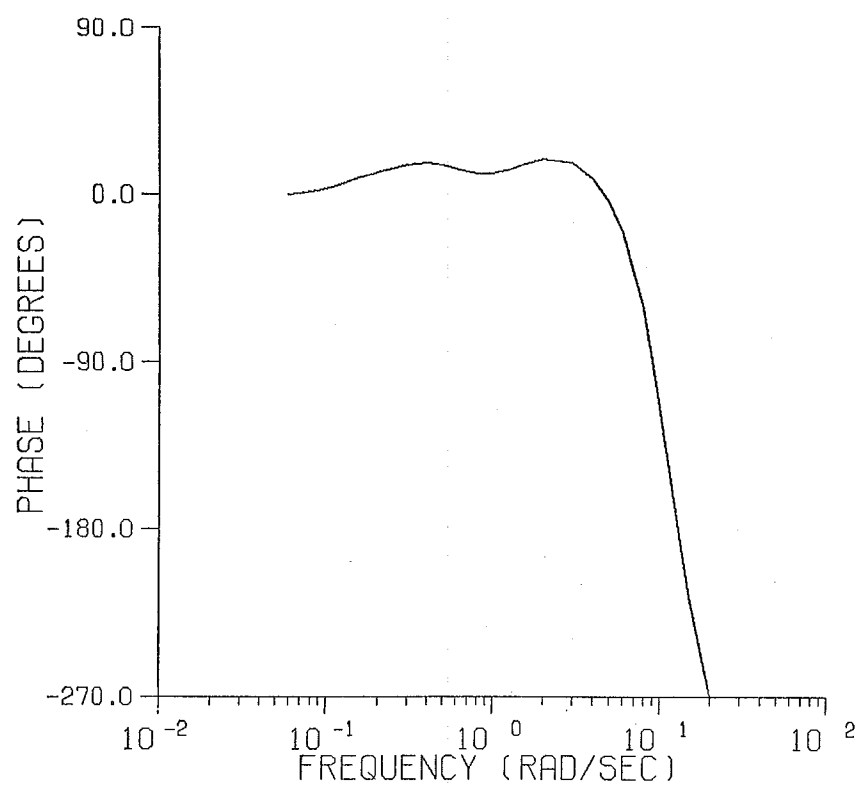
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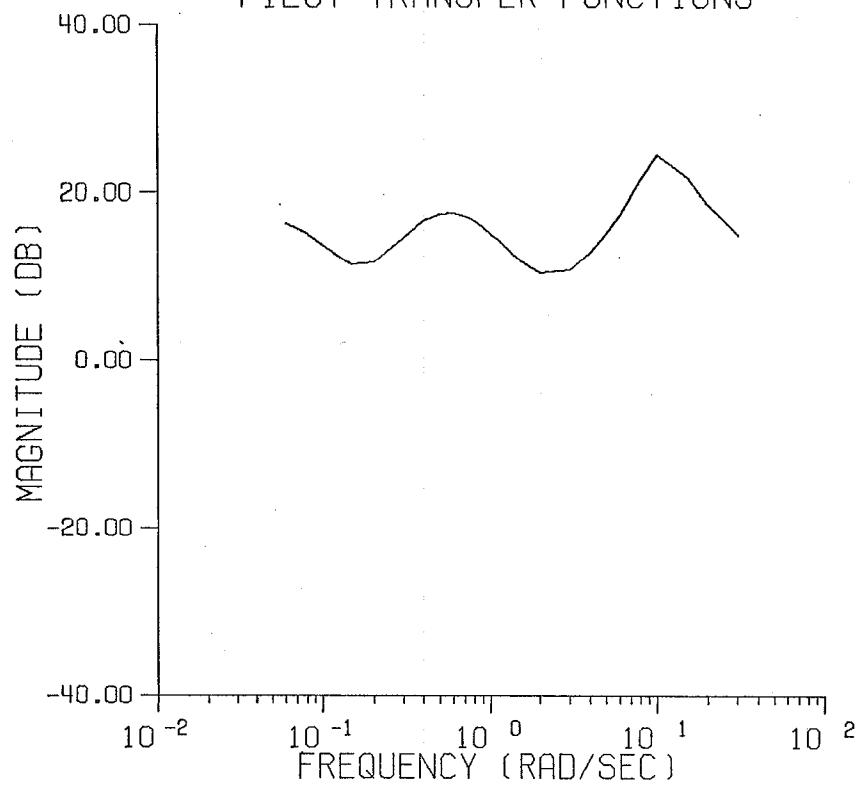
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PILOT TRANSFER FUNCTIONS



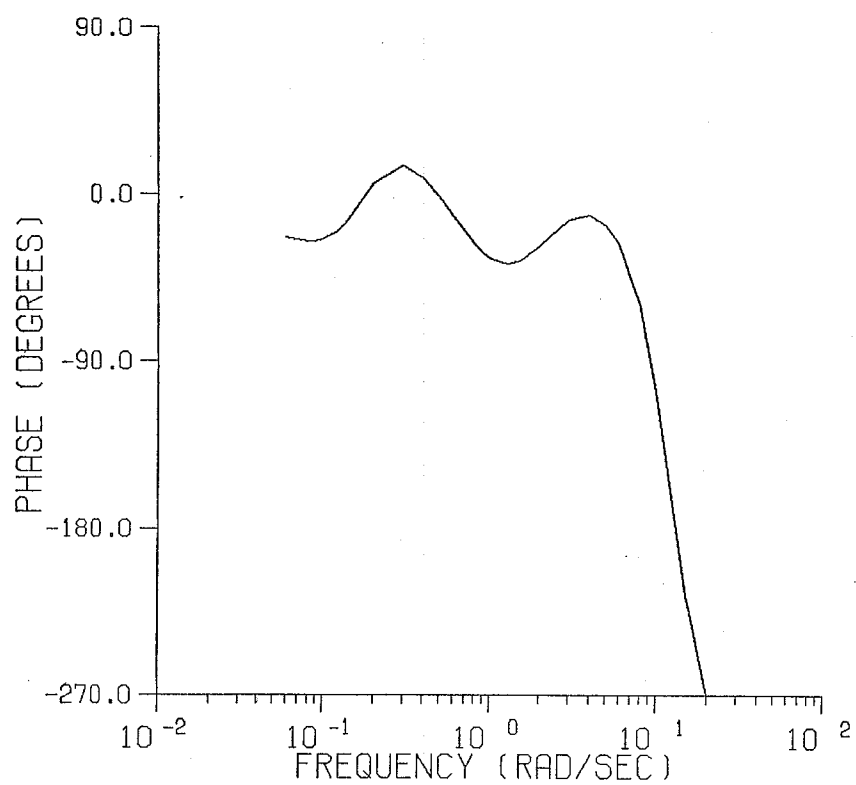
_____ PILOT RESPONSE TO THETA ERROR



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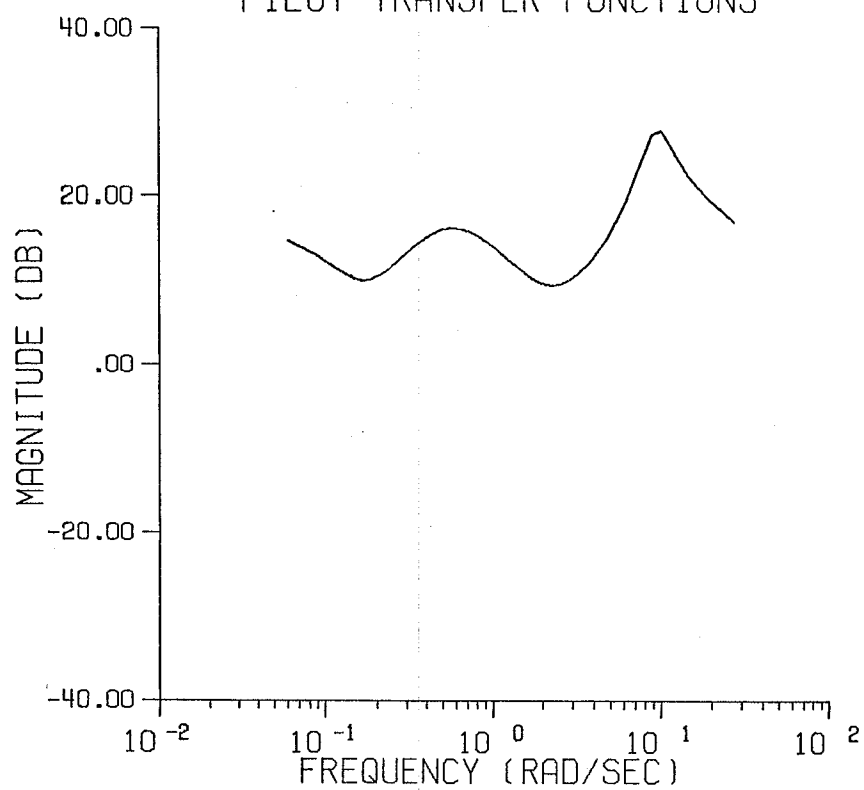


PILOT RESPONSE TO THETA ERROR

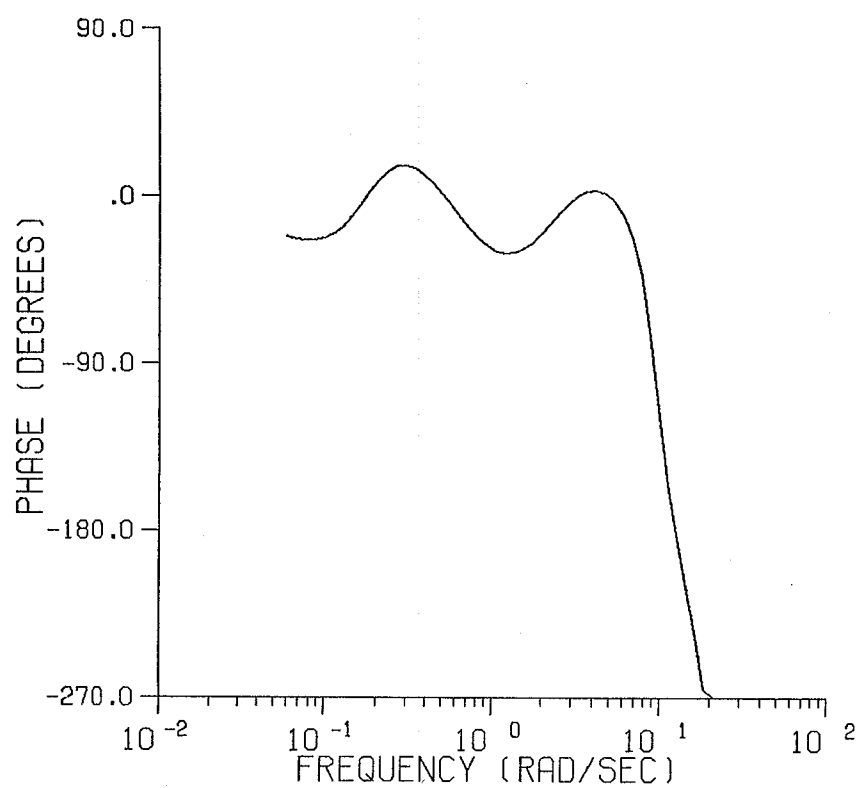


CONFIGURATION 2-2 THETA TRACKING

PILOT TRANSFER FUNCTIONS

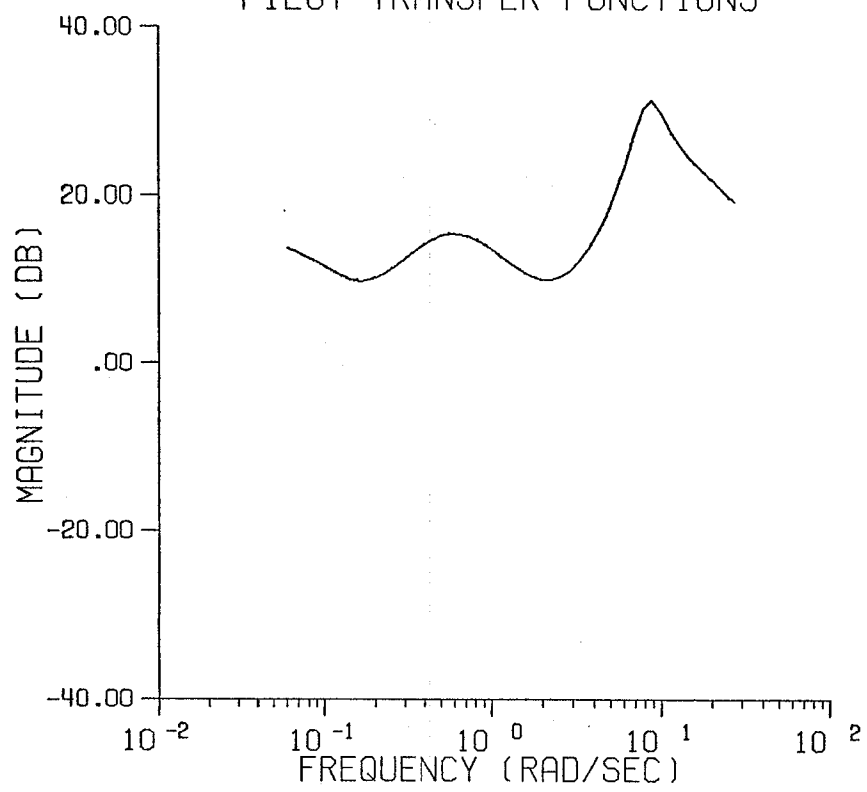


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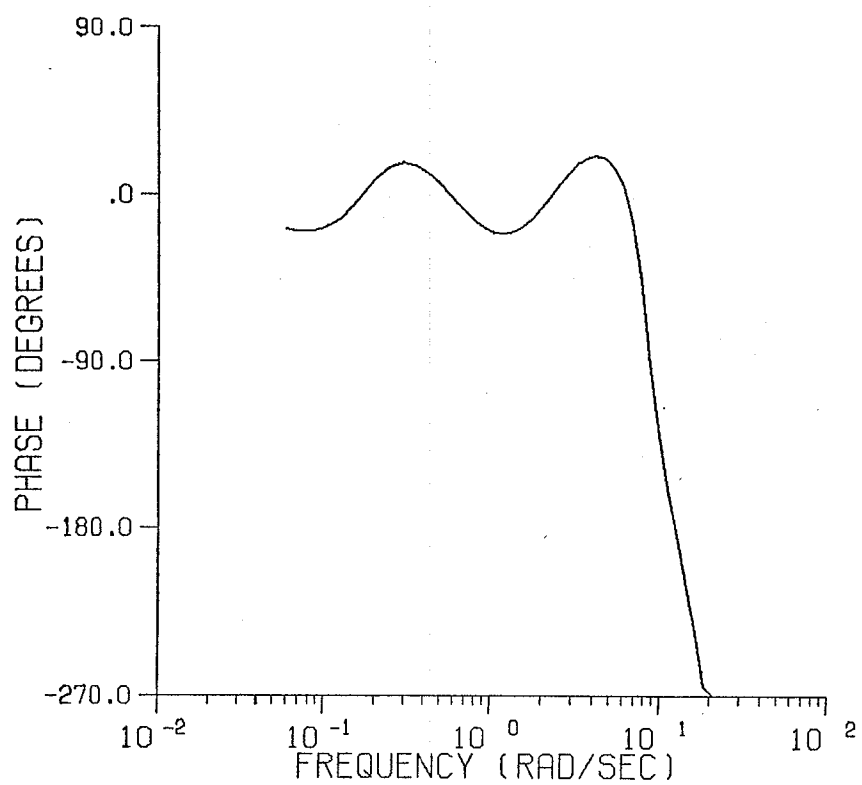


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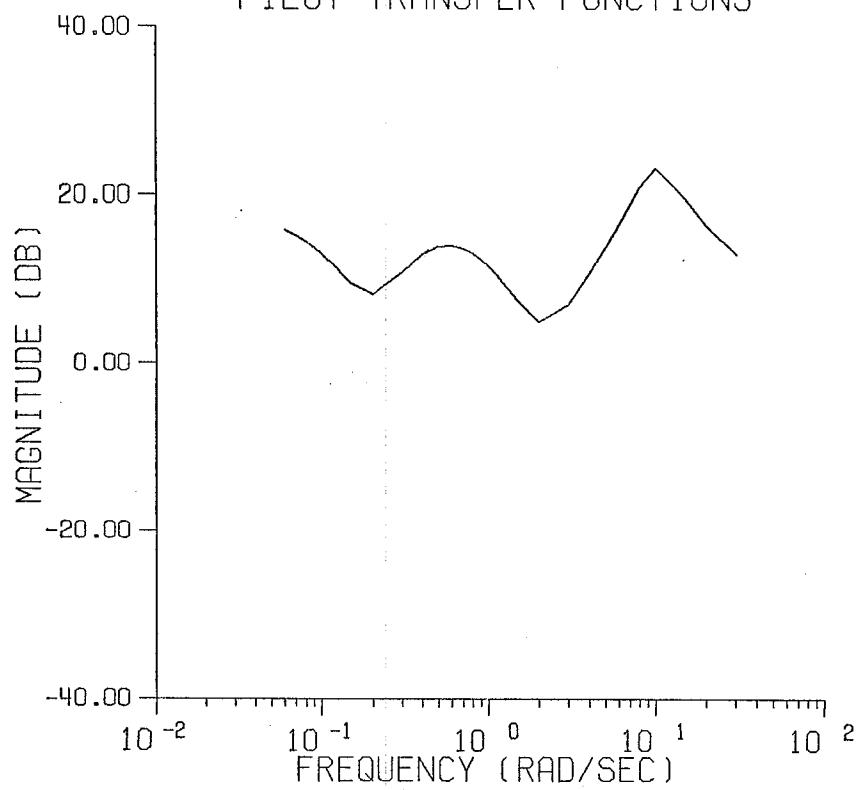
PILOT TRANSFER FUNCTIONS



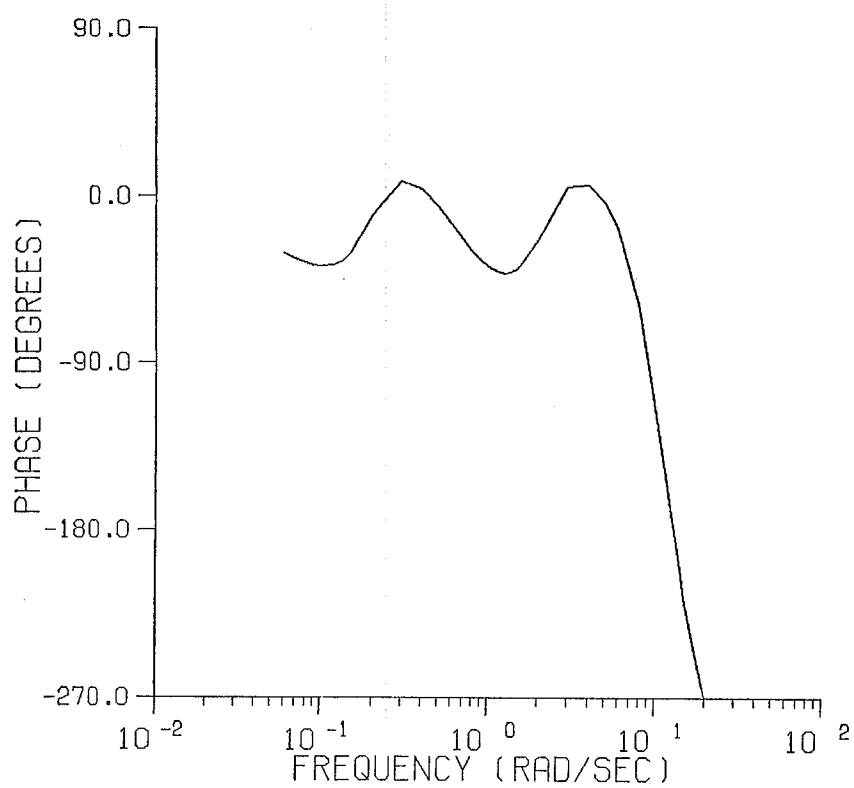
PILOT RESPONSE TO THETA ERROR



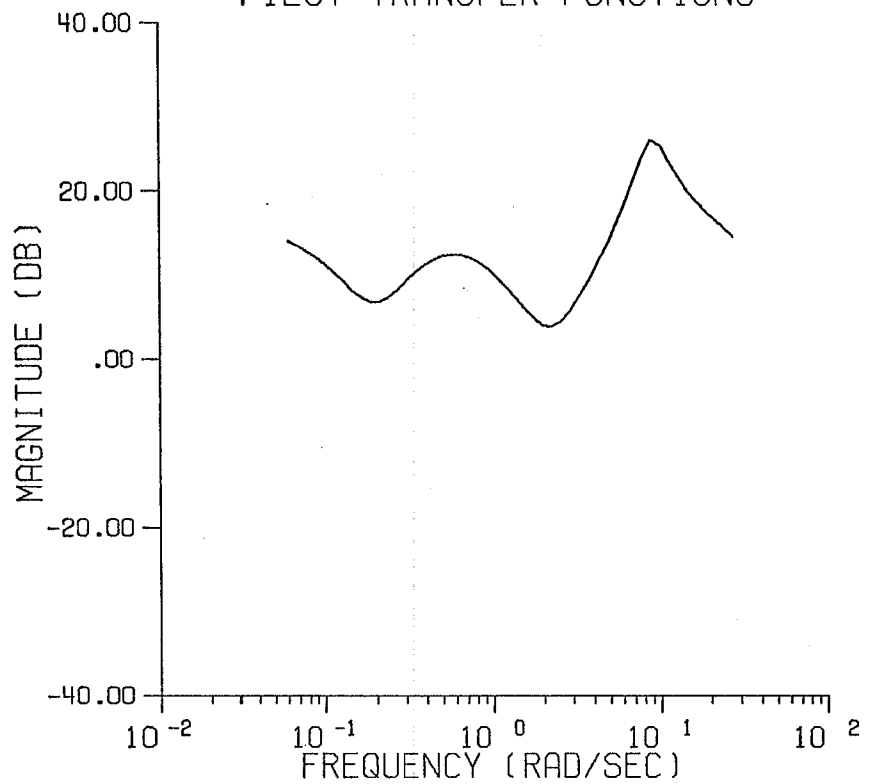
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PILOT TRANSFER FUNCTIONS



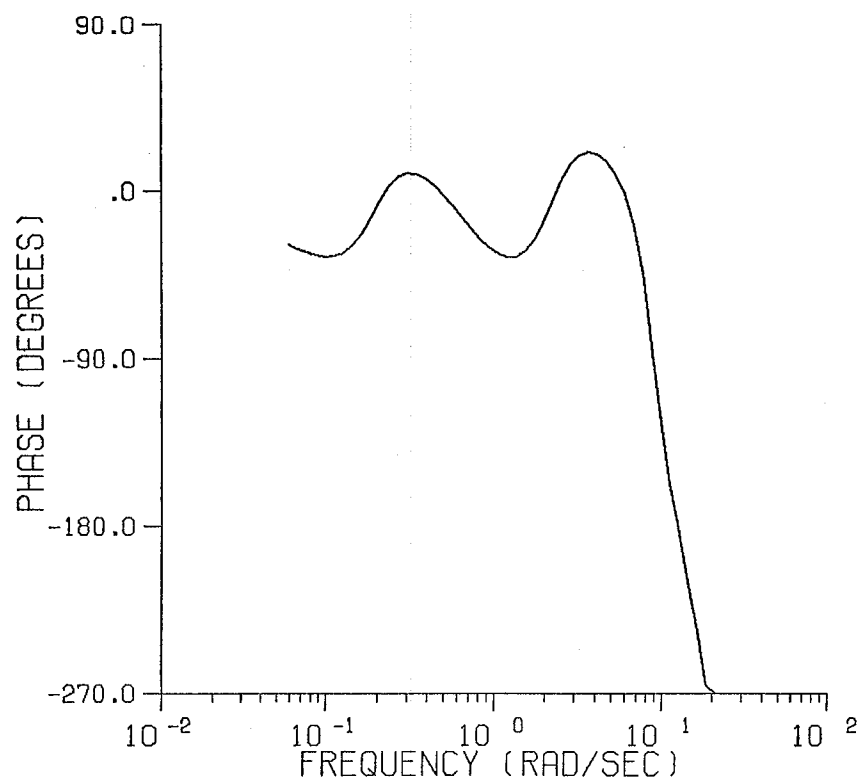
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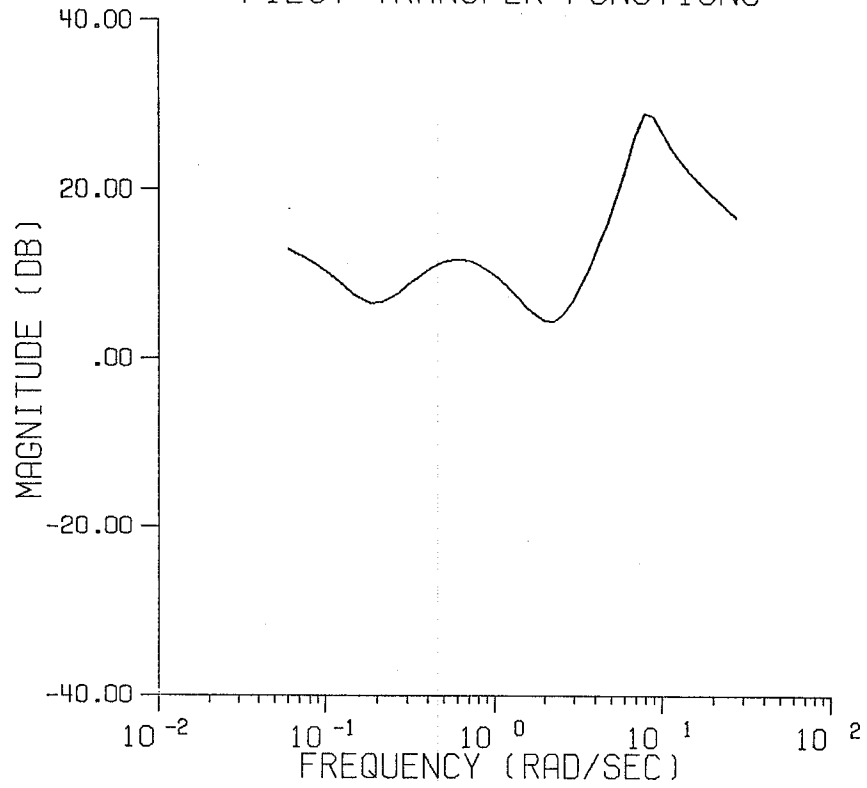
CONFIGURATION 3-2 THETA TRACKING
PILOT TRANSFER FUNCTIONS



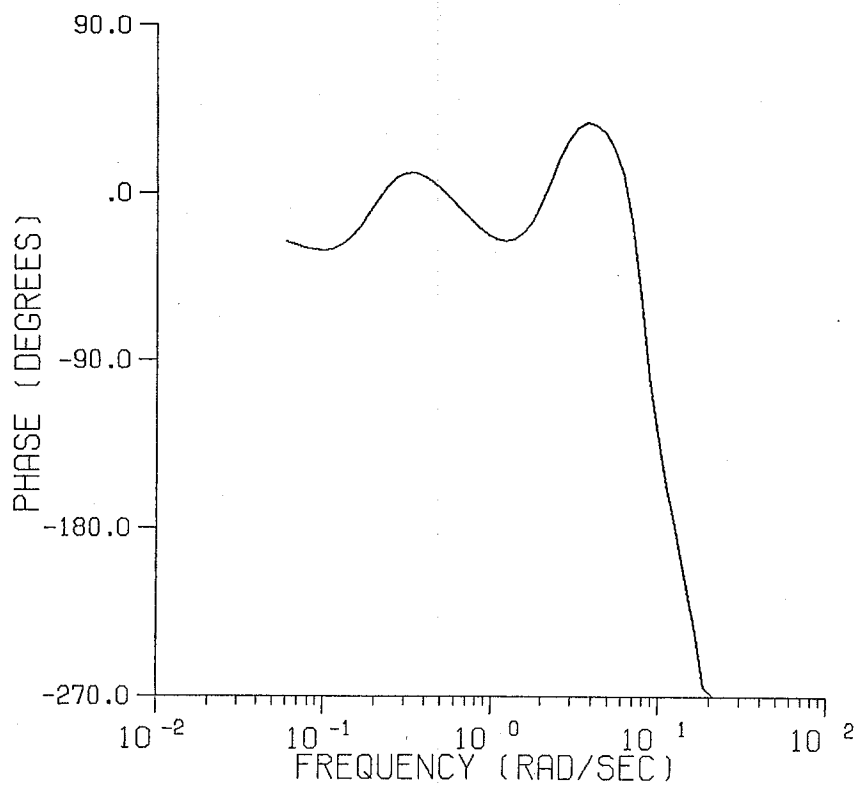
PILOT RESPONSE TO THETA ERROR



CONFIGURATION 3-3 THETA TRACKING
PILOT TRANSFER FUNCTIONS

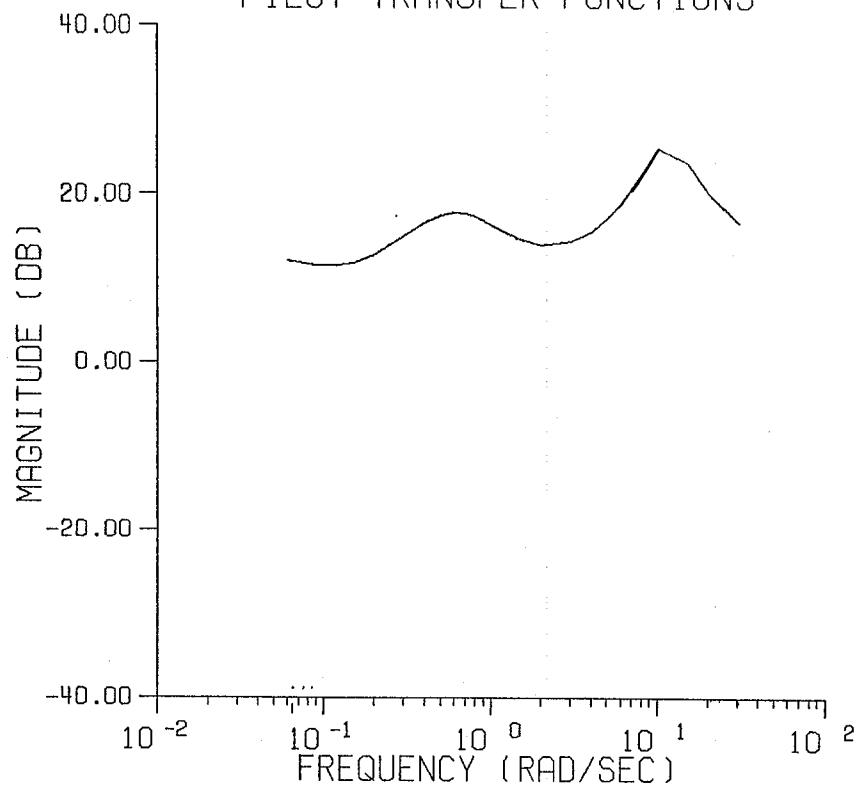


PILOT RESPONSE TO THETA ERROR

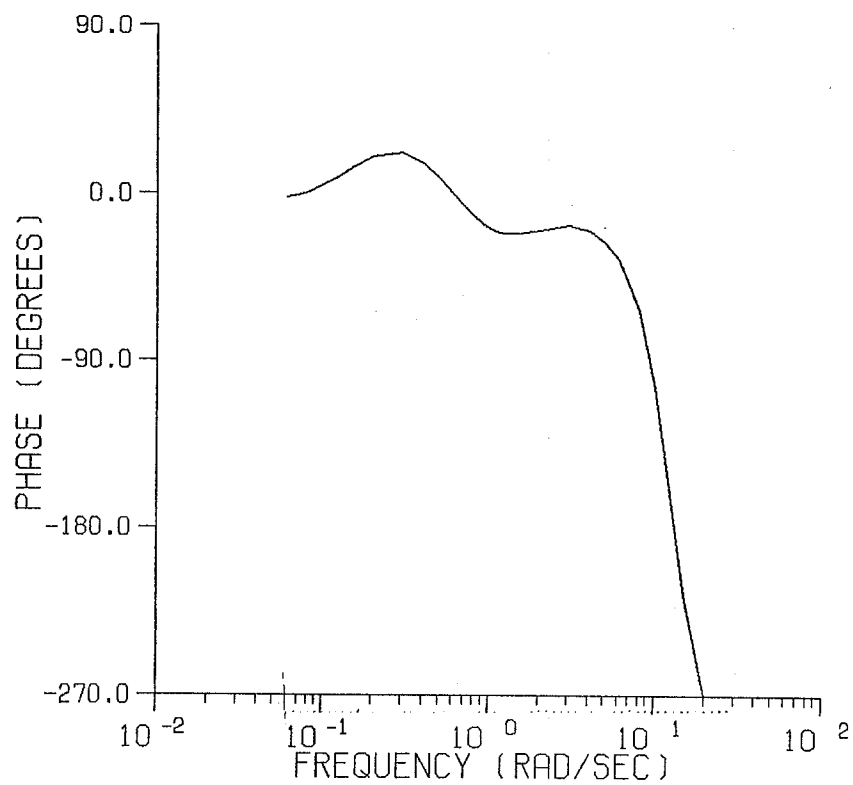


CONFIGURATION 4-1 THETA TRACKING

PILOT TRANSFER FUNCTIONS

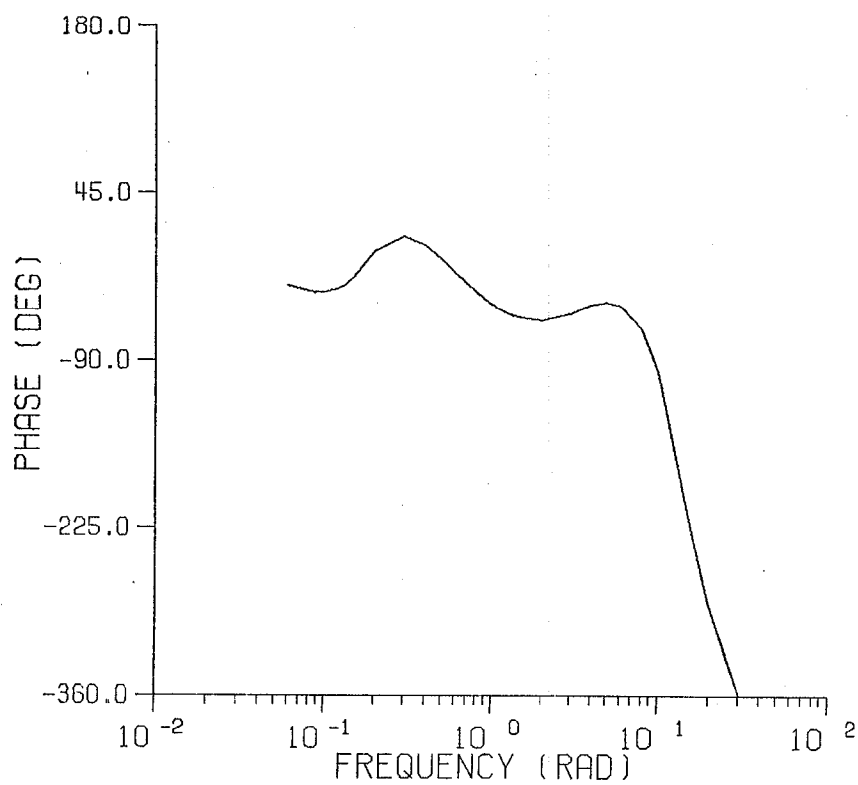
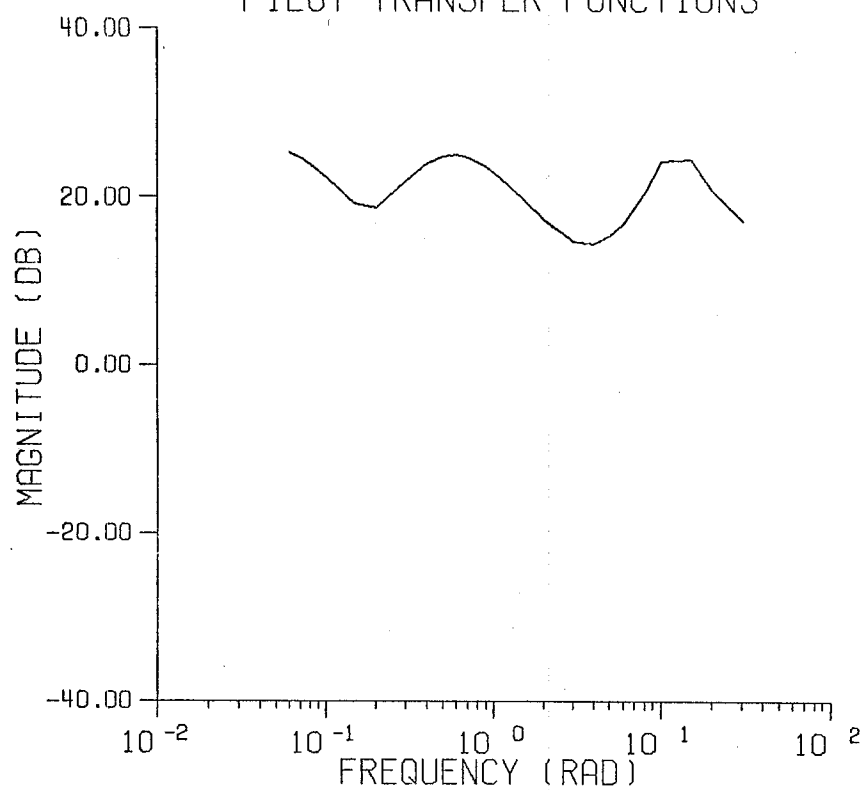


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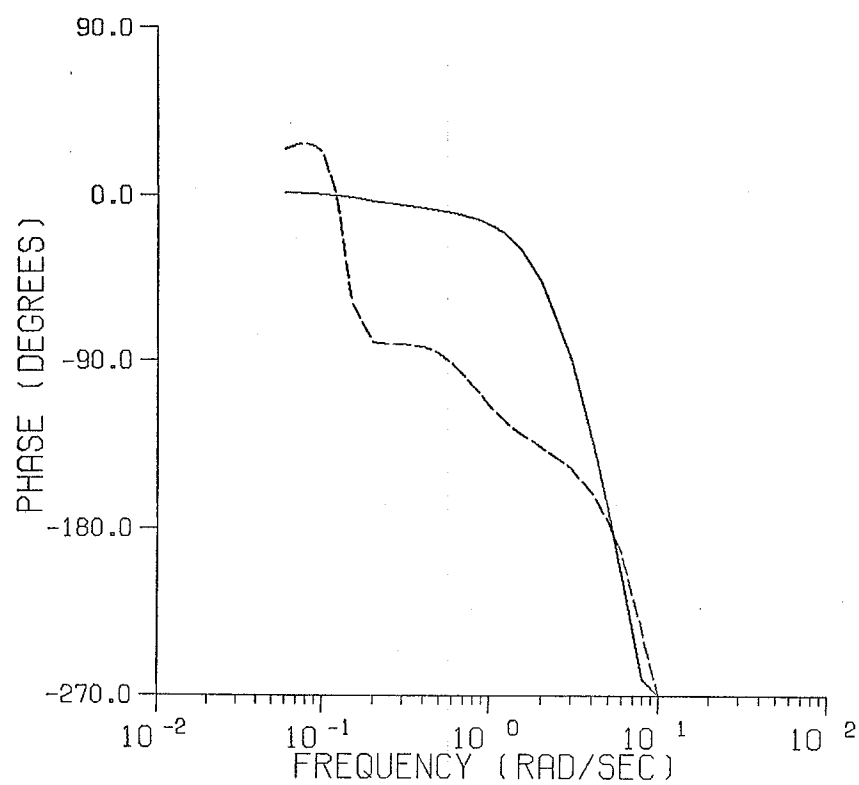
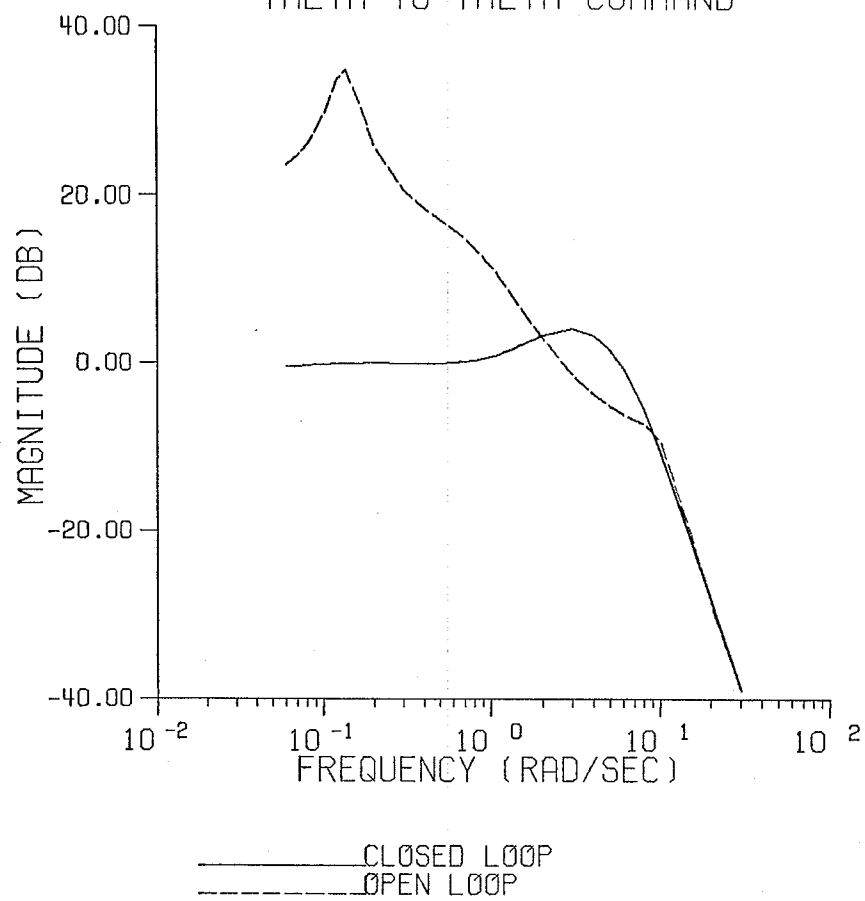
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PILOT TRANSFER FUNCTIONS



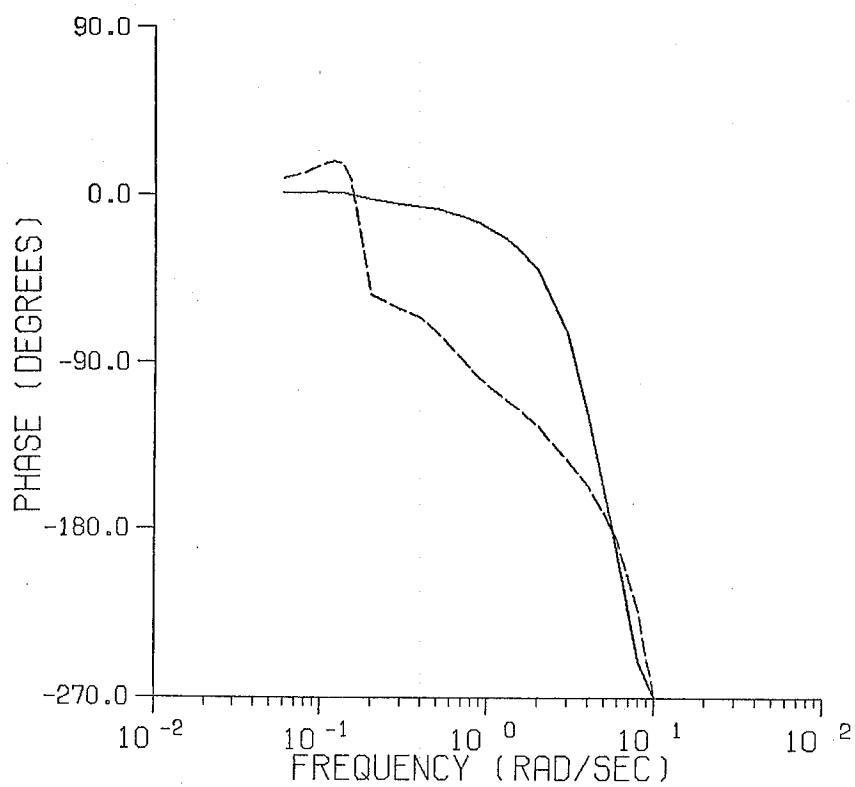
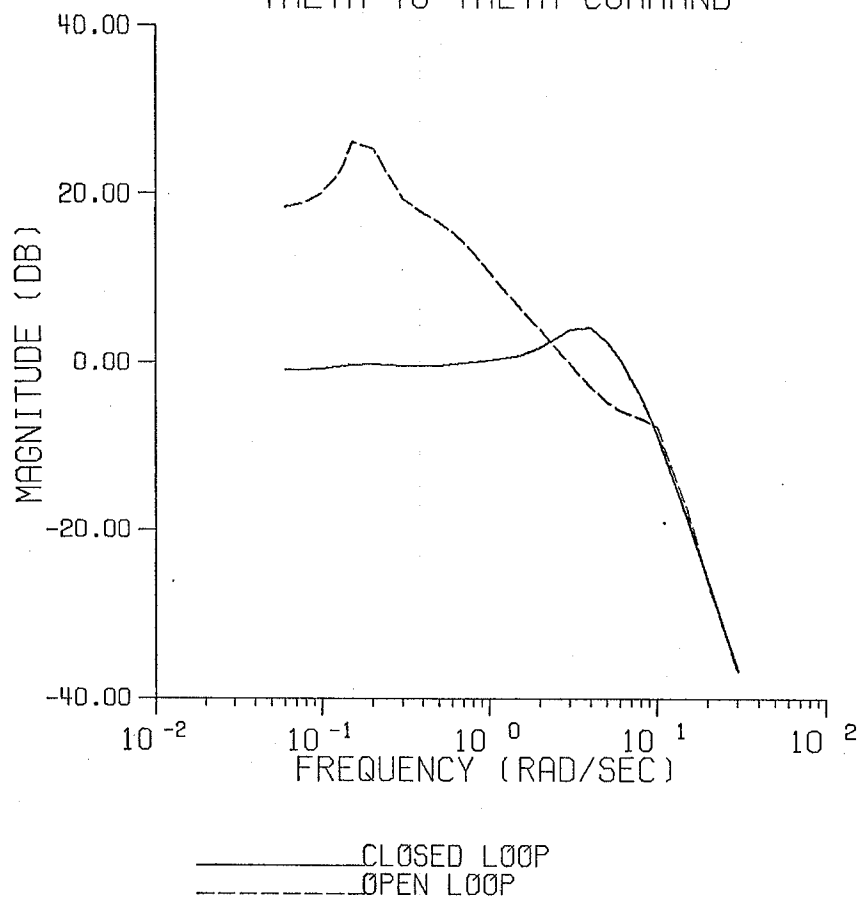
CONFIGURATION 1-1 THETA TRACKING

THETA TO THETA COMMAND



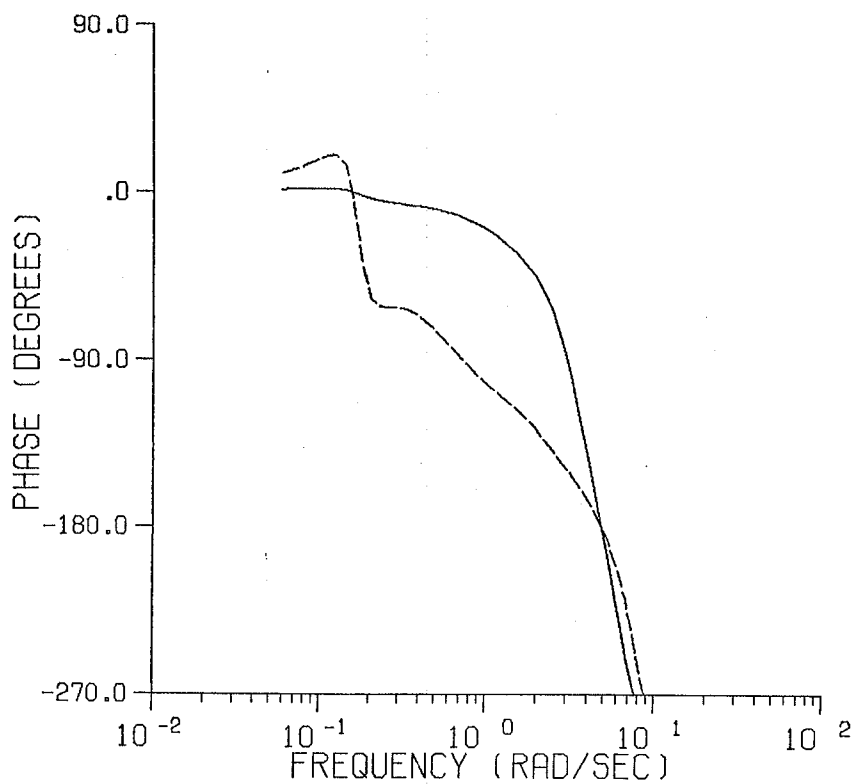
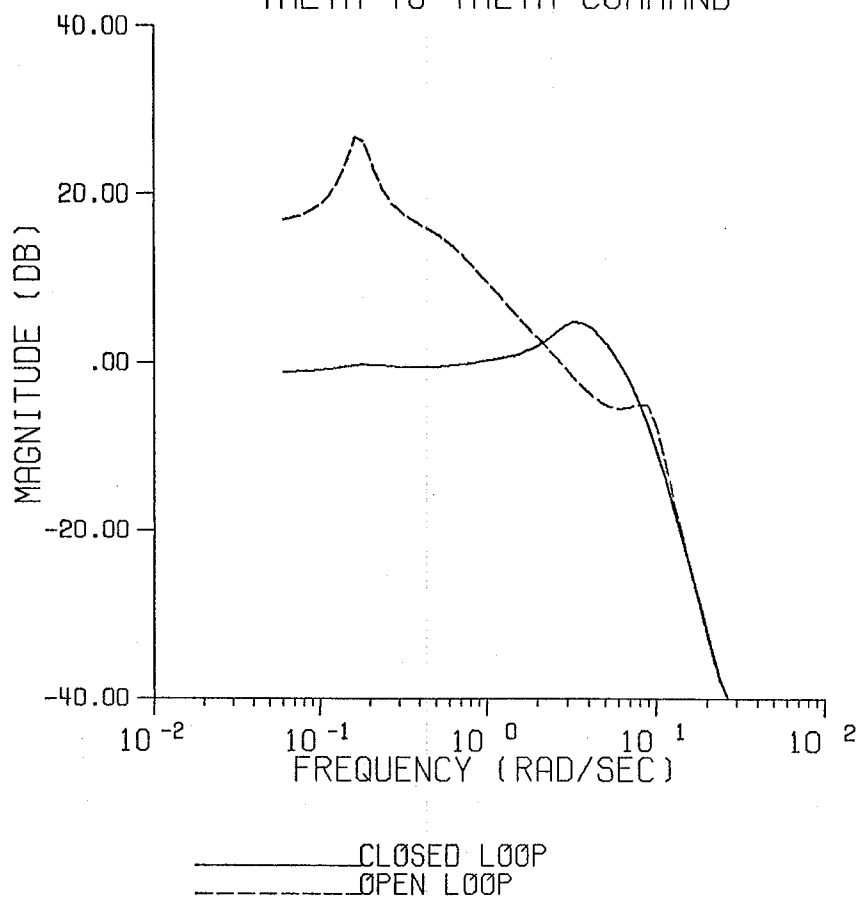
CONFIGURATION 2-1 THETA TRACKING

THETA TO THETA COMMAND



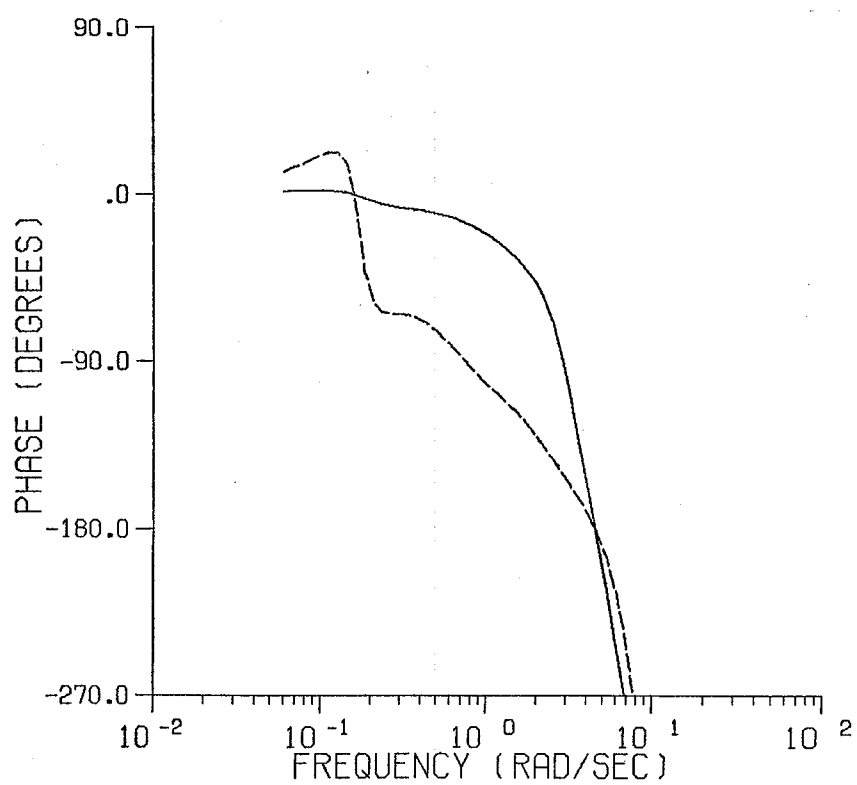
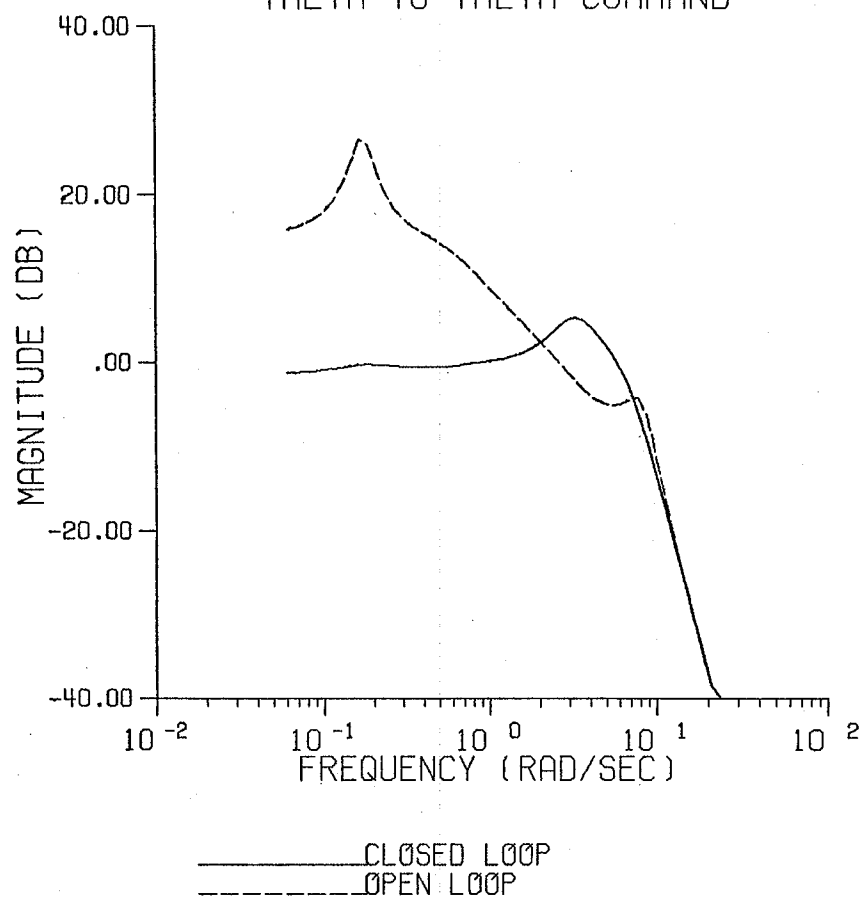
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THETA TO THETA COMMAND



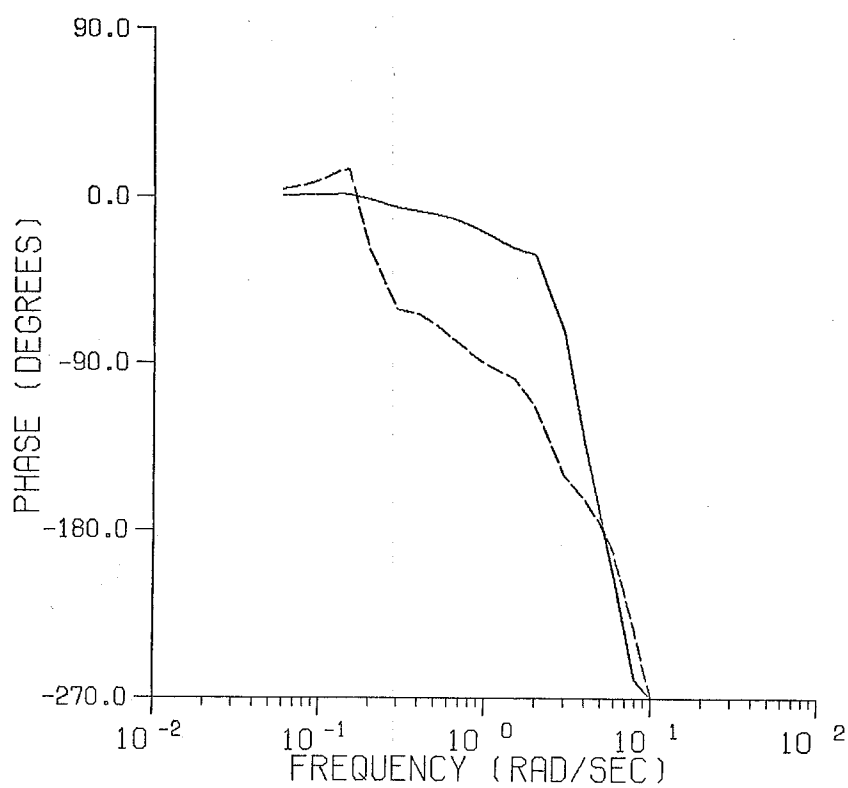
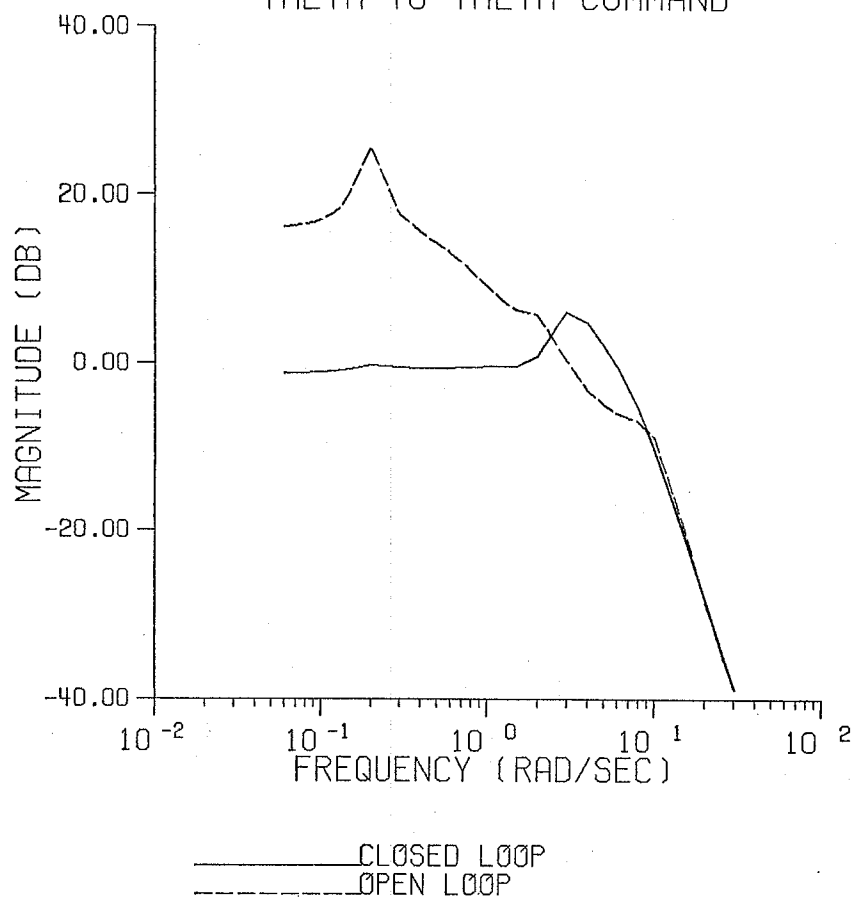
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THETA TO THETA COMMAND



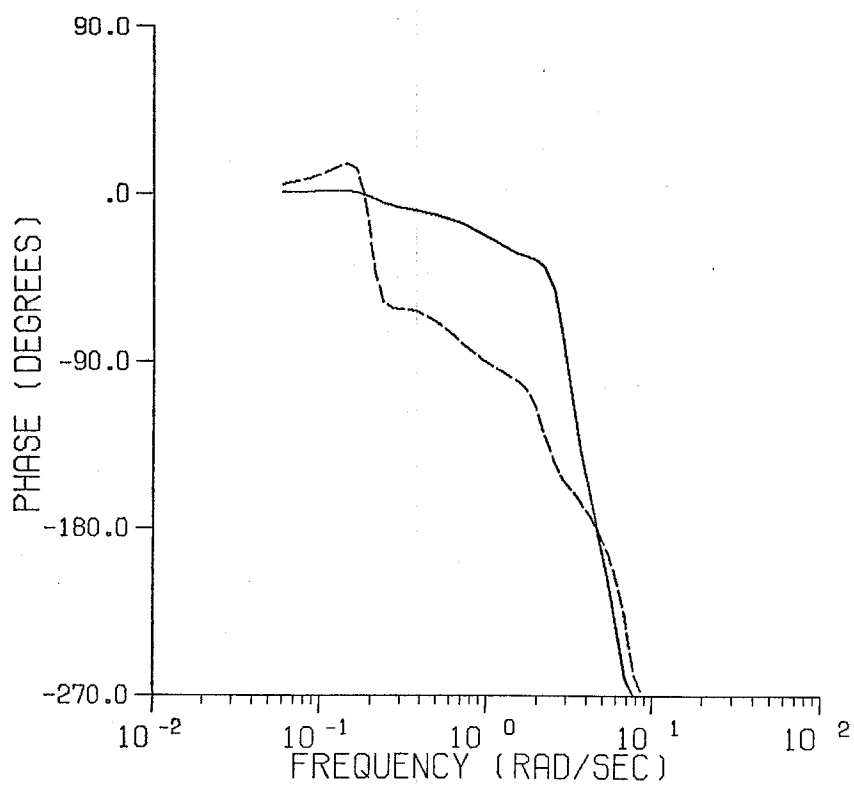
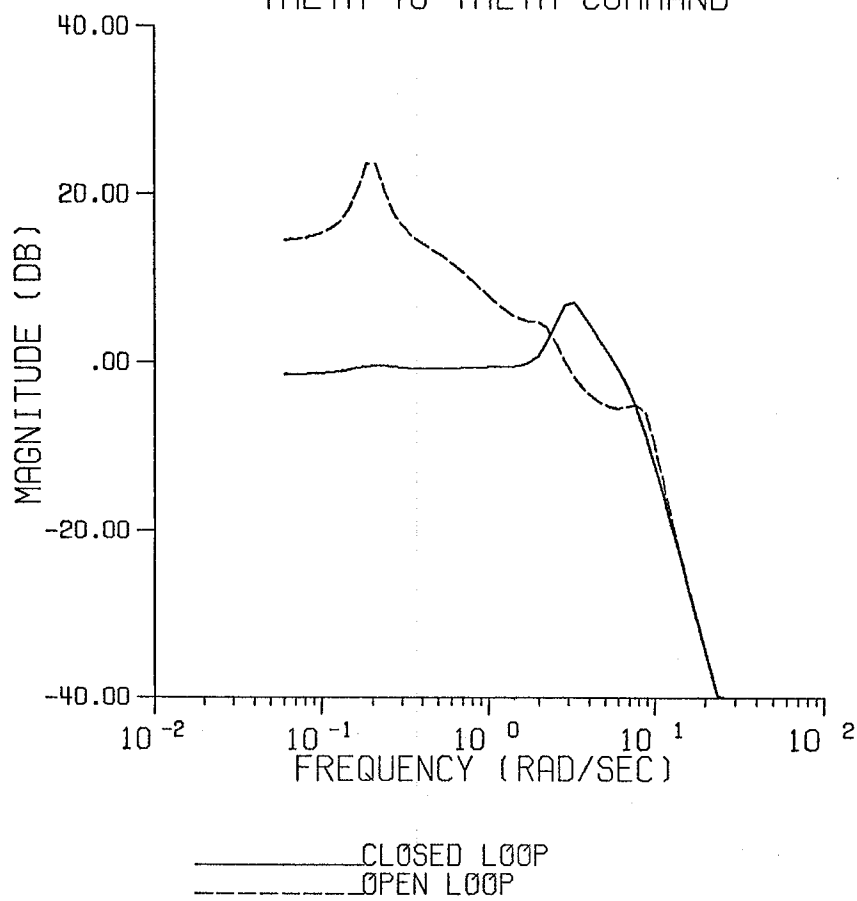
CONFIGURATION 3-1 THETA TRACKING

THETA TO THETA COMMAND



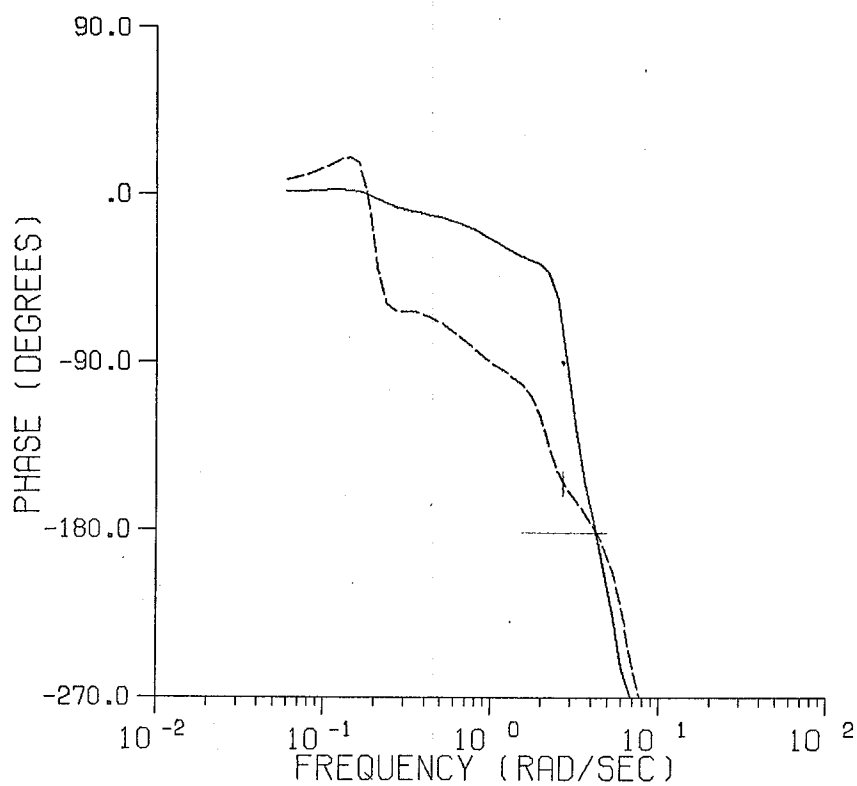
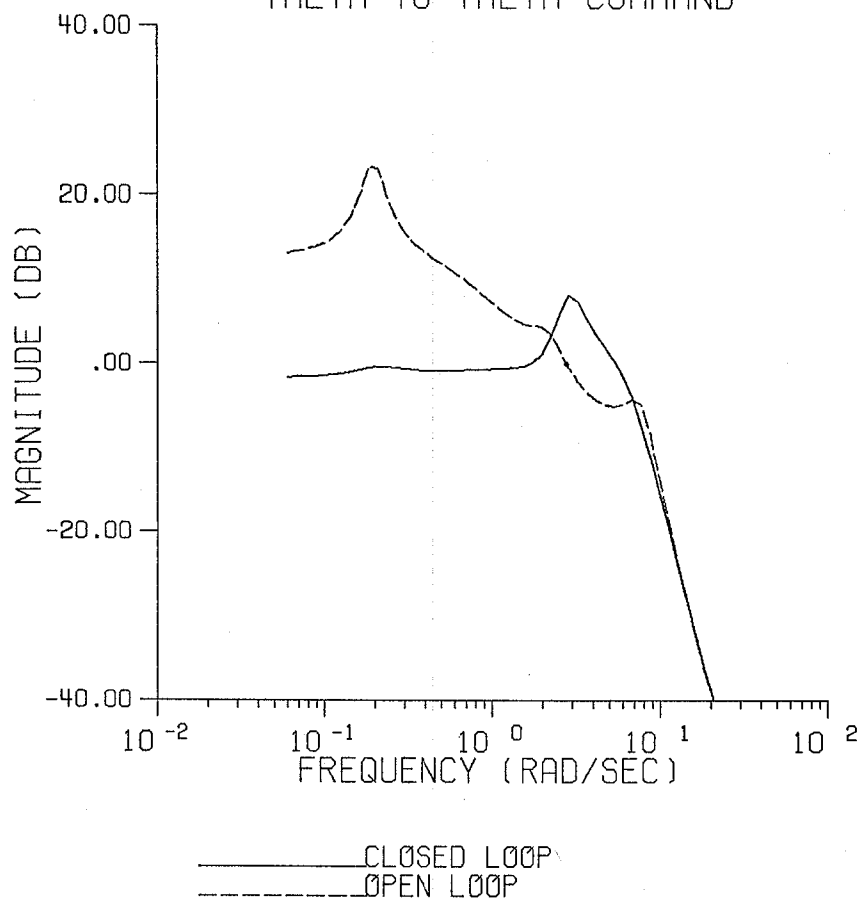
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THETA TO THETA COMMAND



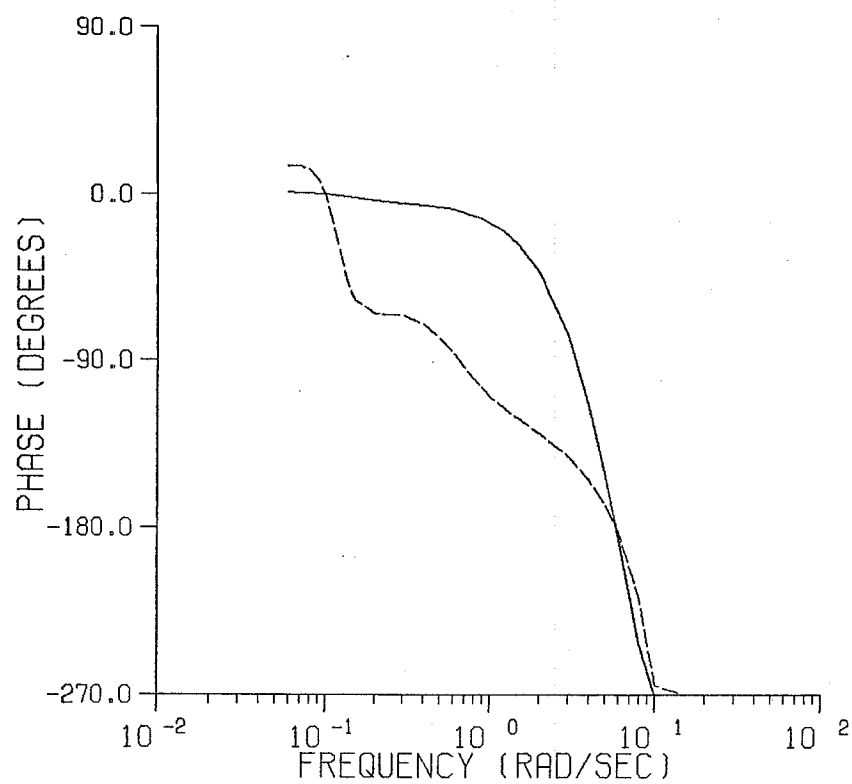
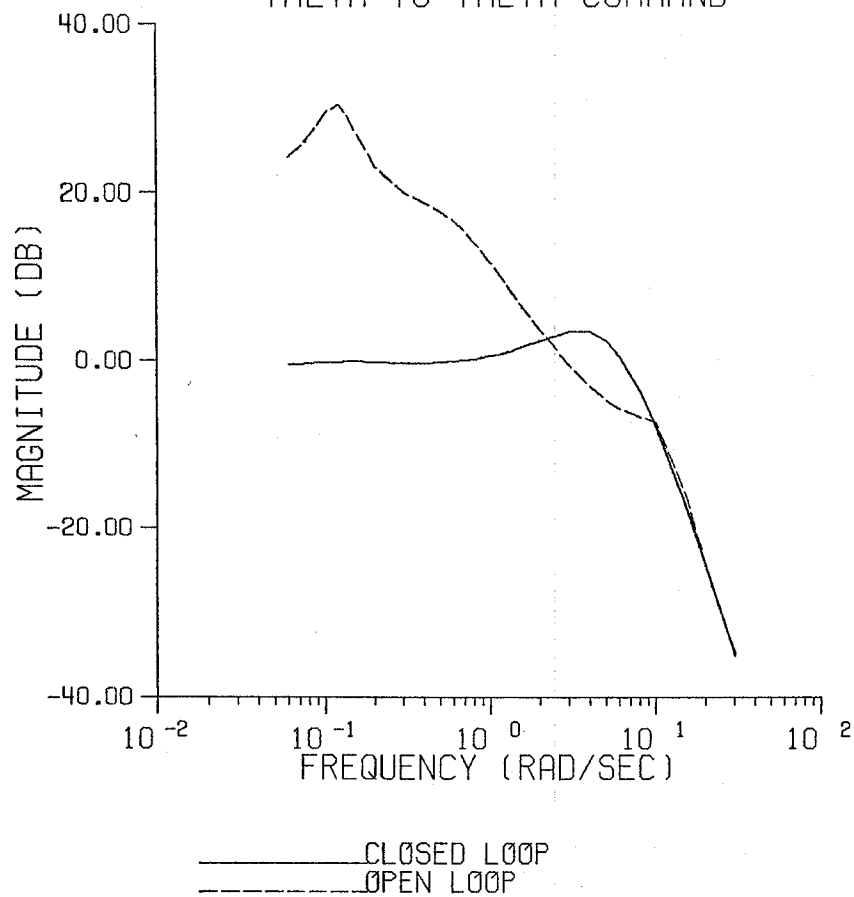
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THETA TO THETA COMMAND



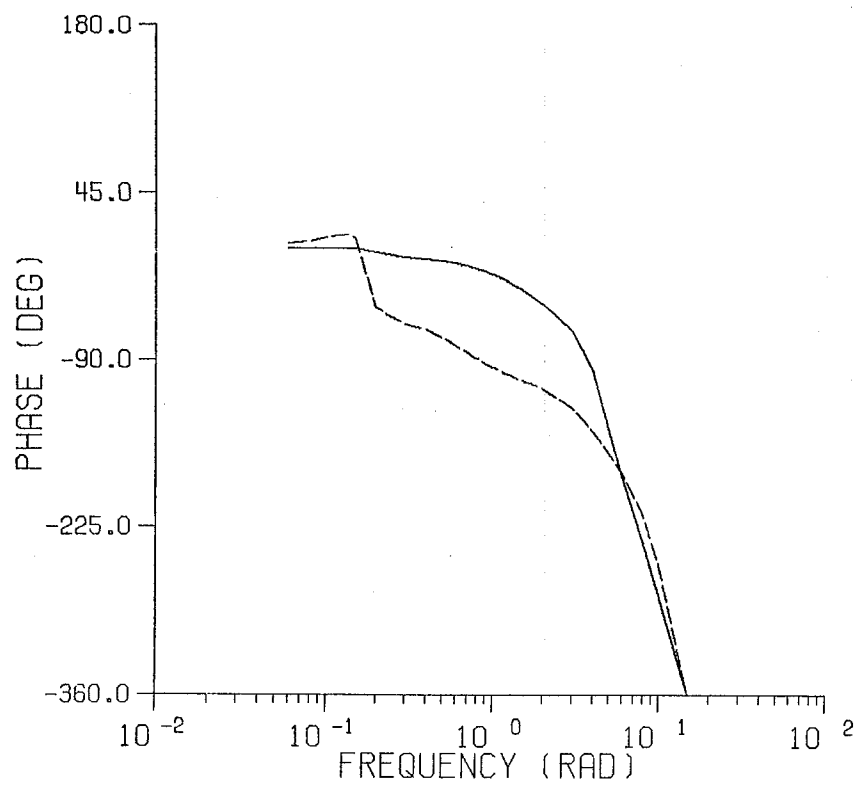
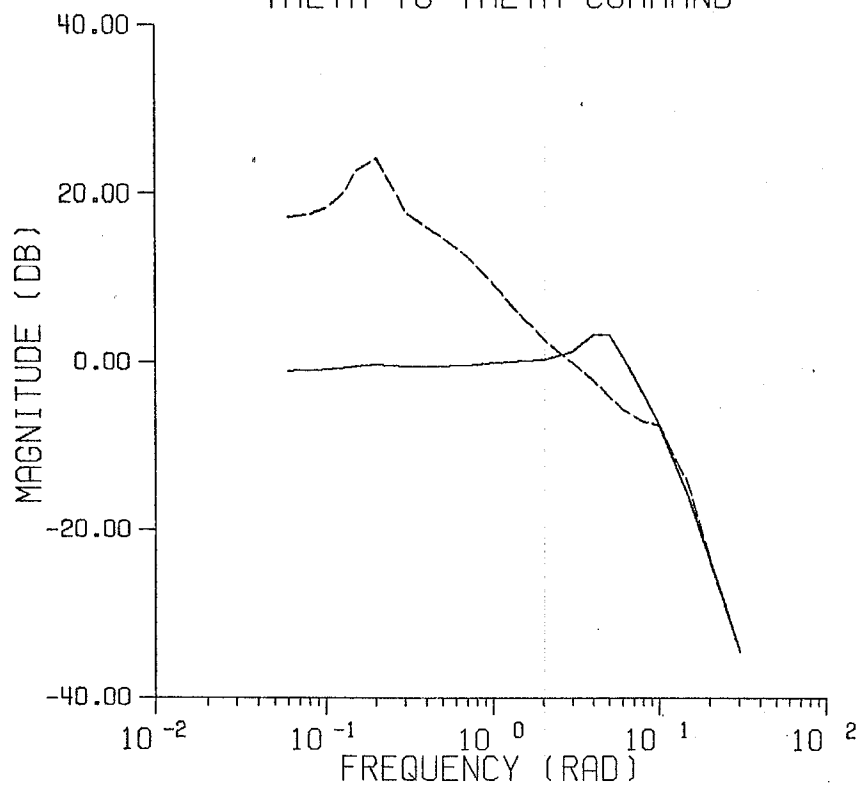
CONFIGURATION 4-1 THETA TRACKING

THETA TO THETA COMMAND



CONFIGURATION 5-1 THETA TRACKING

THETA TO THETA COMMAND



FLIGHT PATH ANGLE TRACKING

CONFIGURATION	BANDWIDTH	P.O.R.
1-1	2.011	4
2-1	1.990	2
2-2	1.875	4
2-3	1.793	6
3-1	1.975	5.5
3-2	1.828	7
3-3	1.744	10
4-1	1.958	2
5-1	1.924	6

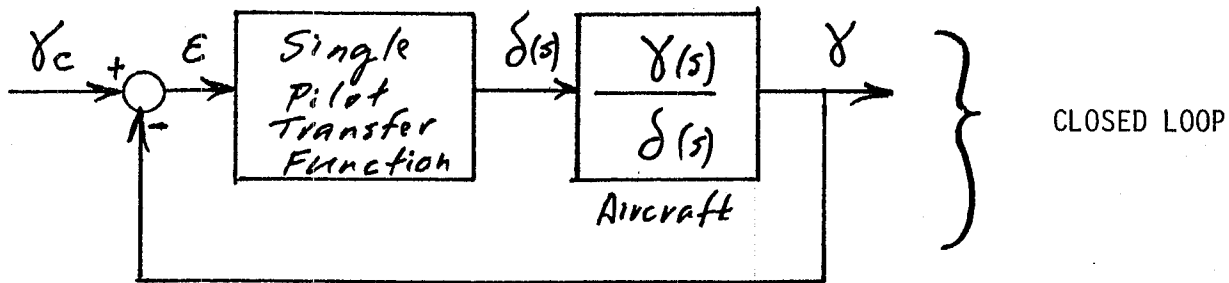
CONFIGURATION	SENSITIVITY (db)	SENSITIVITY (ABS)
1-1	1.464	3.083
2-1	.925	1.834
2-2	1.693	3.430
2-3	1.853	3.737
3-1	2.364	4.282
3-2	1.704	3.089
3-3	1.742	3.163
4-1	1.008	2.114
5-1	1.108	2.213

FLIGHT PATH ANGLE TRACKING

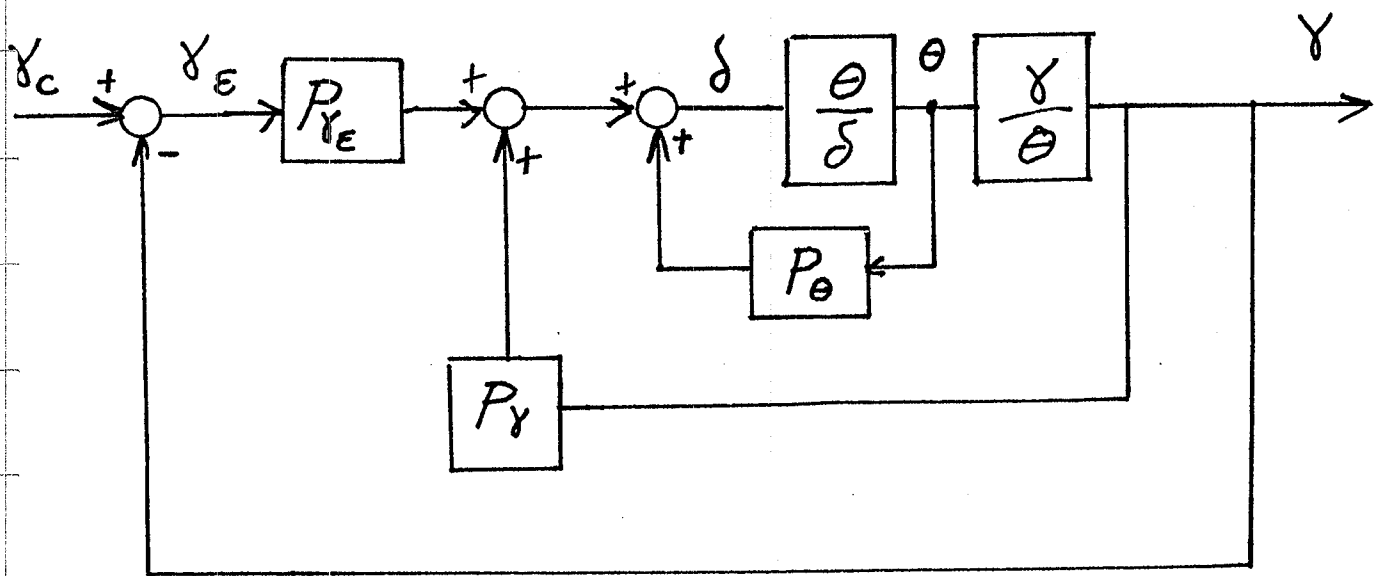
CONFIGURATION	PILOT γ_{ERROR} COMP. (AT BANDWIDTH)	SINGLE PILOT TRANSFER FOR COMP. (AT BANDWIDTH)
1-1	57.440	71.459
2-1	15.757	16.037
2-2	21.379	20.805
2-3	30.484	30.451
3-1	12.149	7.502
3-2	13.578	3.965
3-3	21.356	9.833
4-1	29.249	31.501
5-1	-17.424	-21.836

CONFIGURATION	RESONANT PEAK
1-1	6.365
2-1	5.963
2-2	5.979
2-3	5.905
3-1	4.863
3-2	5.010
3-3	5.016
4-1	6.427
5-1	5.982

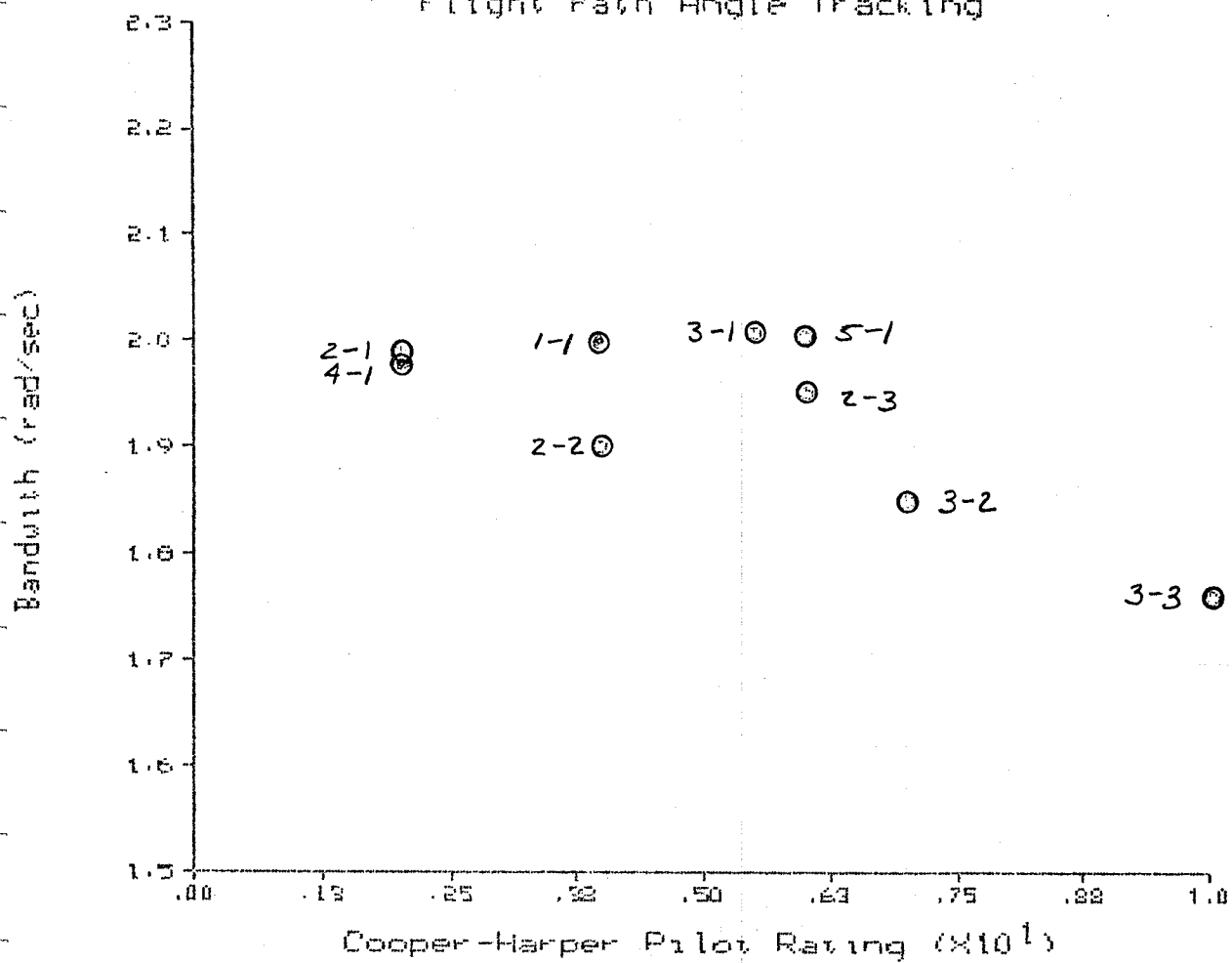
'Single Pilot Transfer Function' Definition



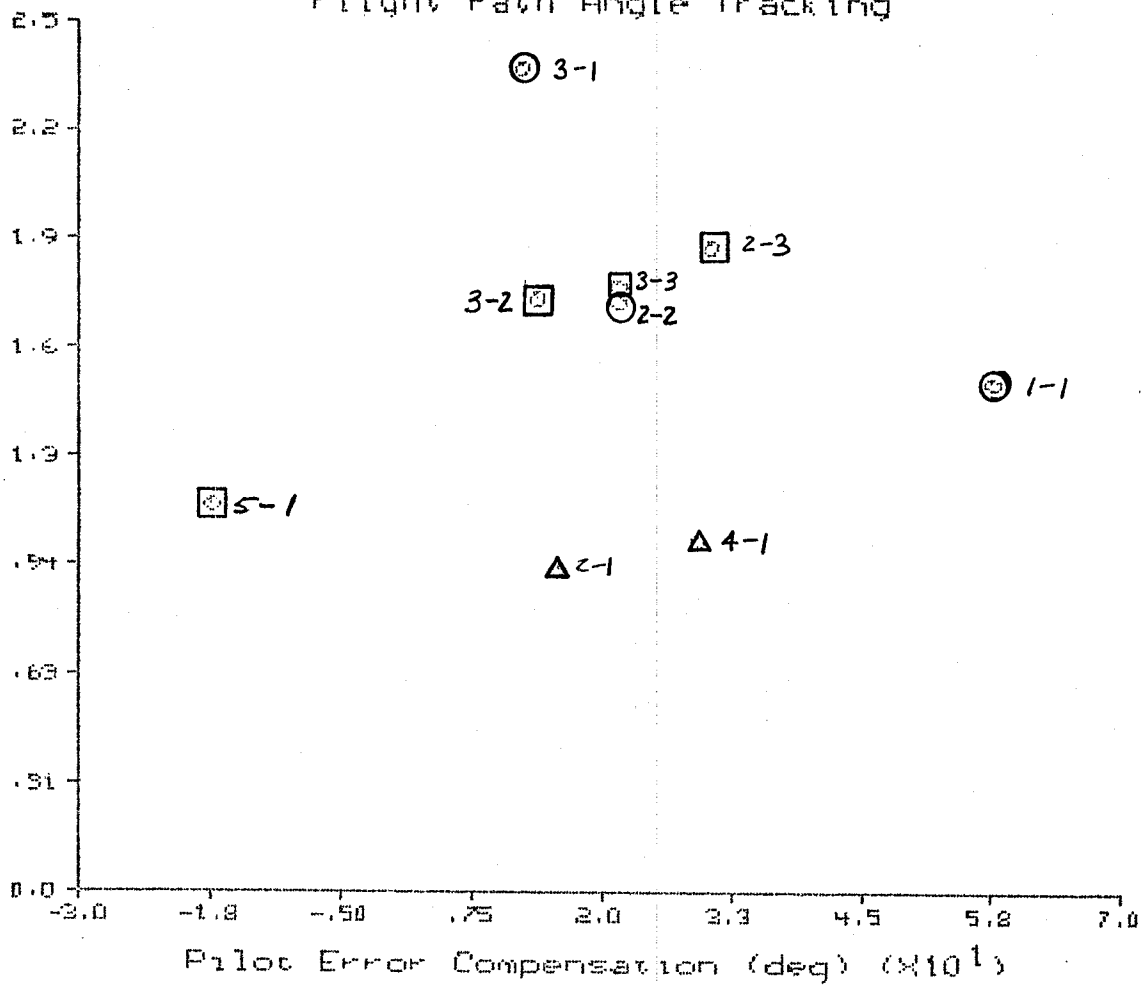
same closed loop response.



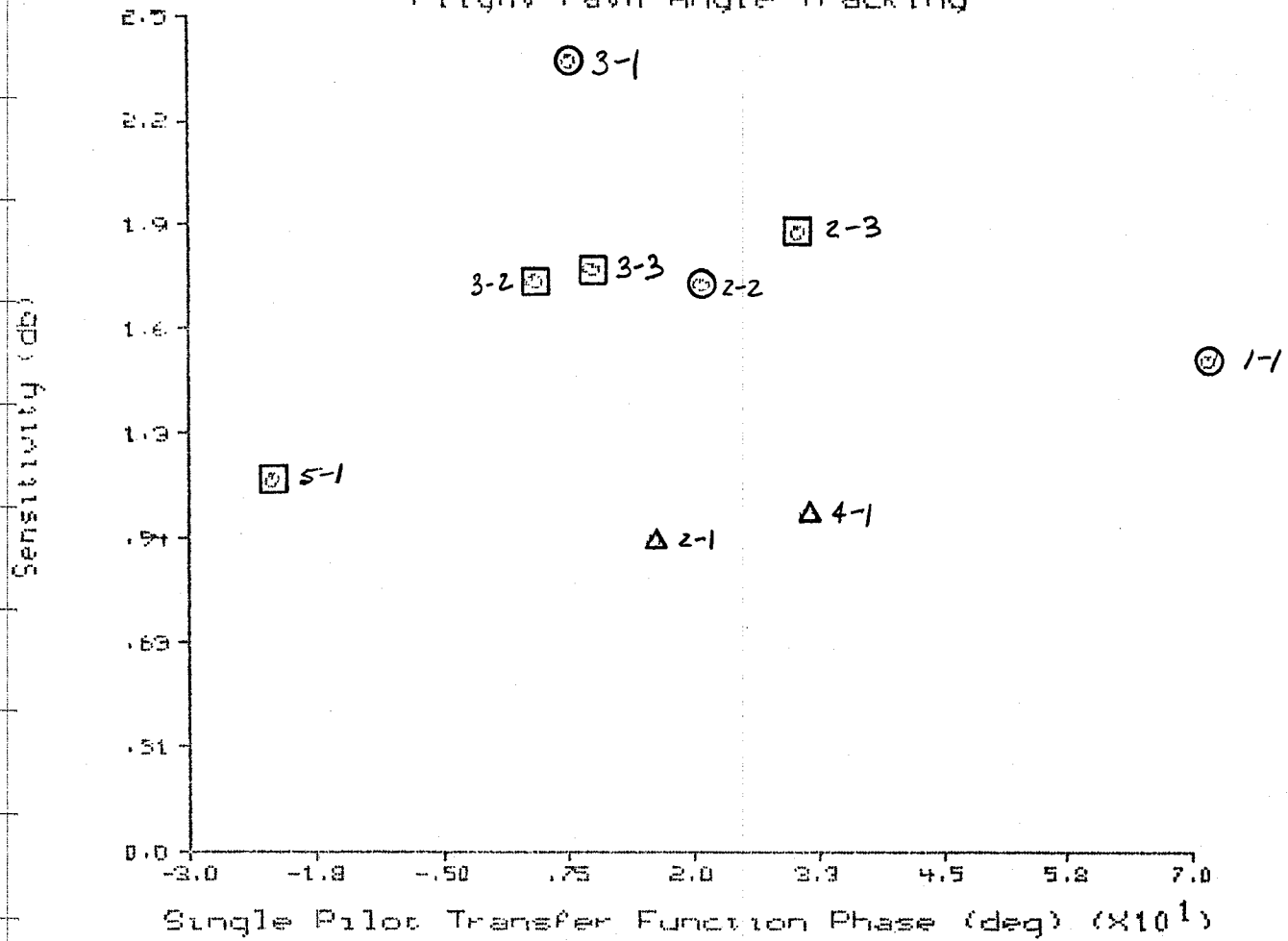
Flight Path Angle Tracking



Flight Path Angle Tracking

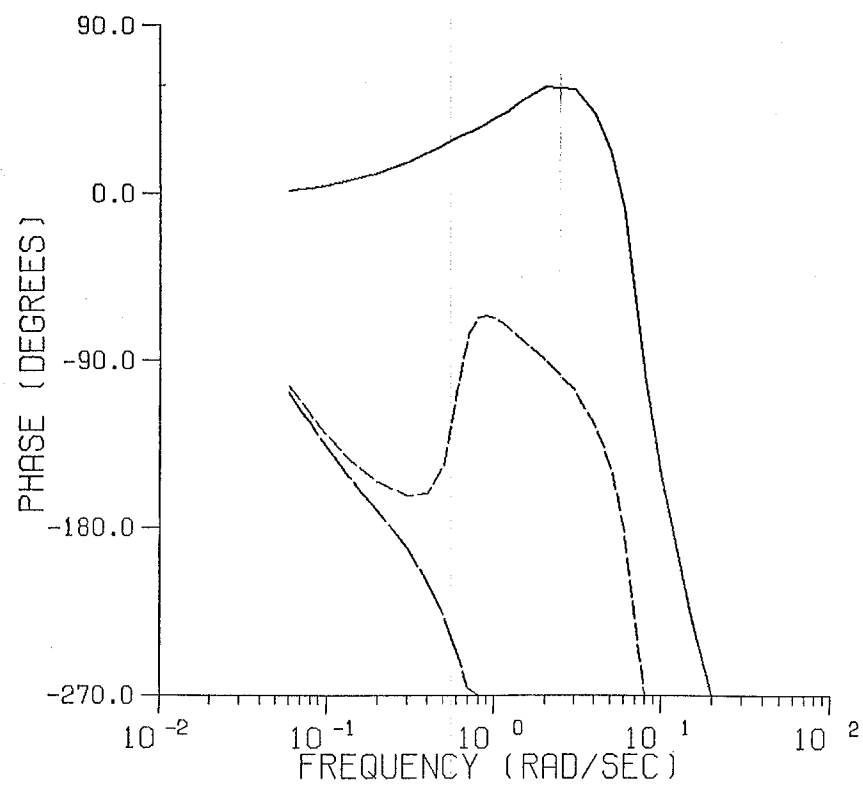
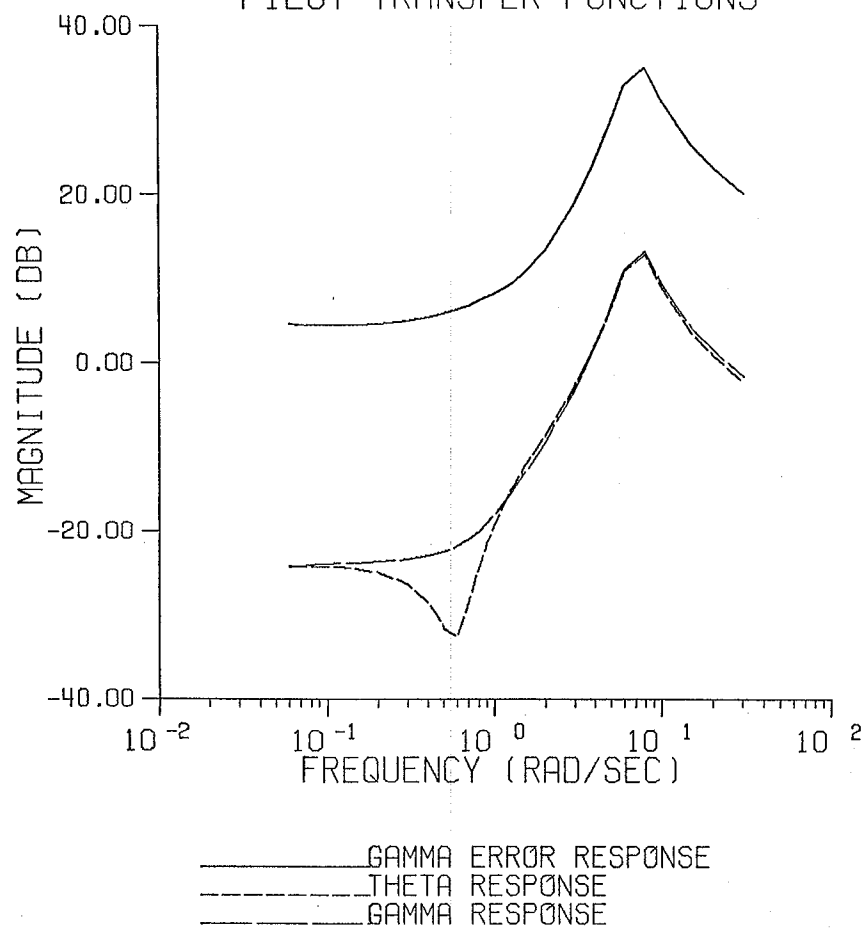


Flight Path Angle Tracking



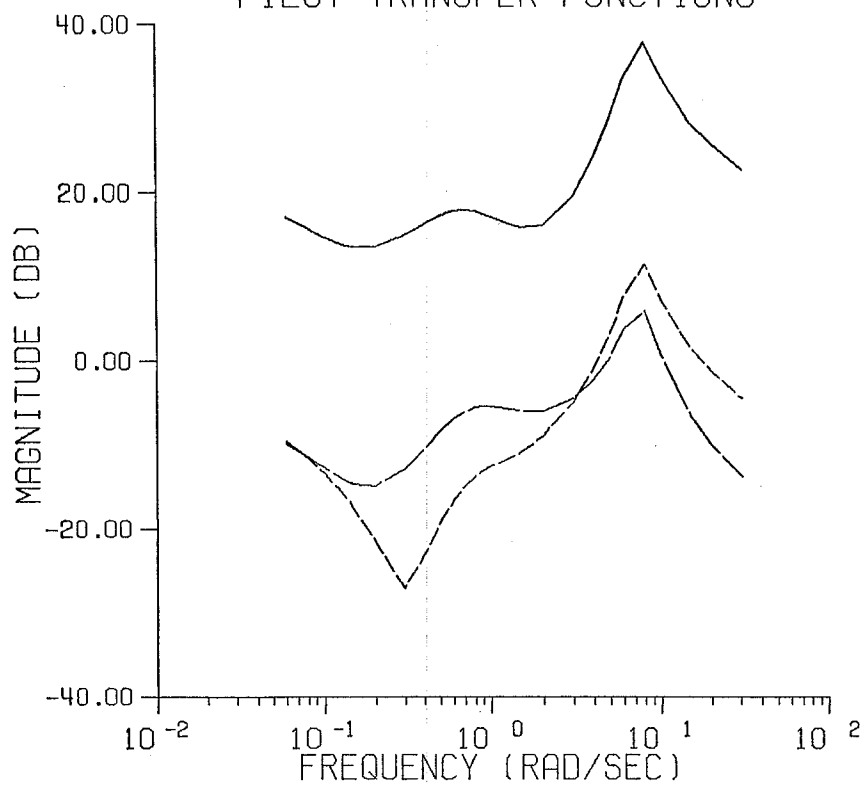
CONFIGURATION 1-1 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS

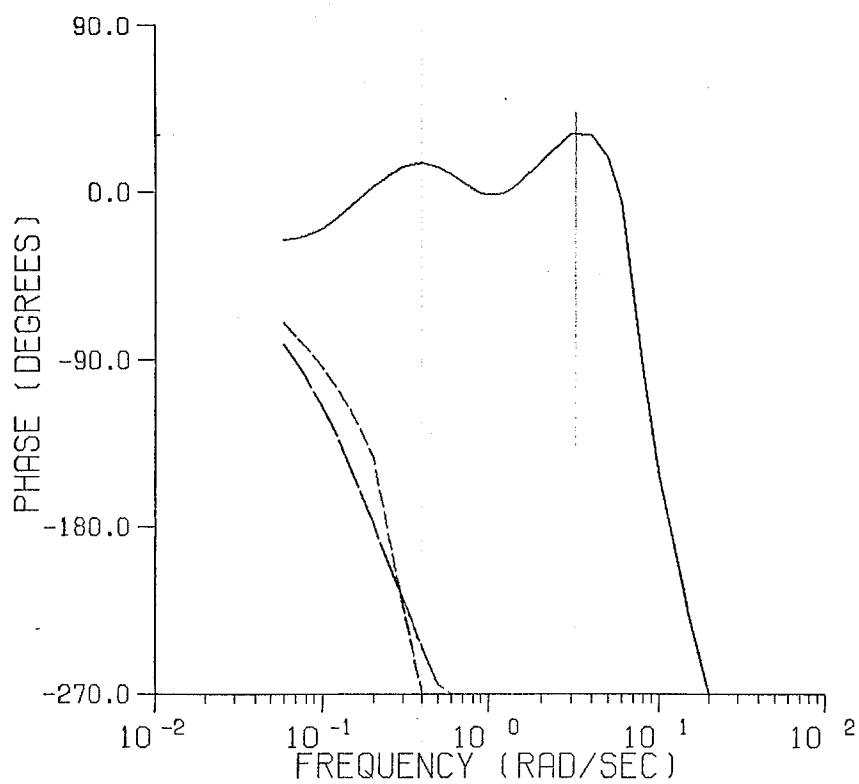


CONFIGURATION 2-1 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS

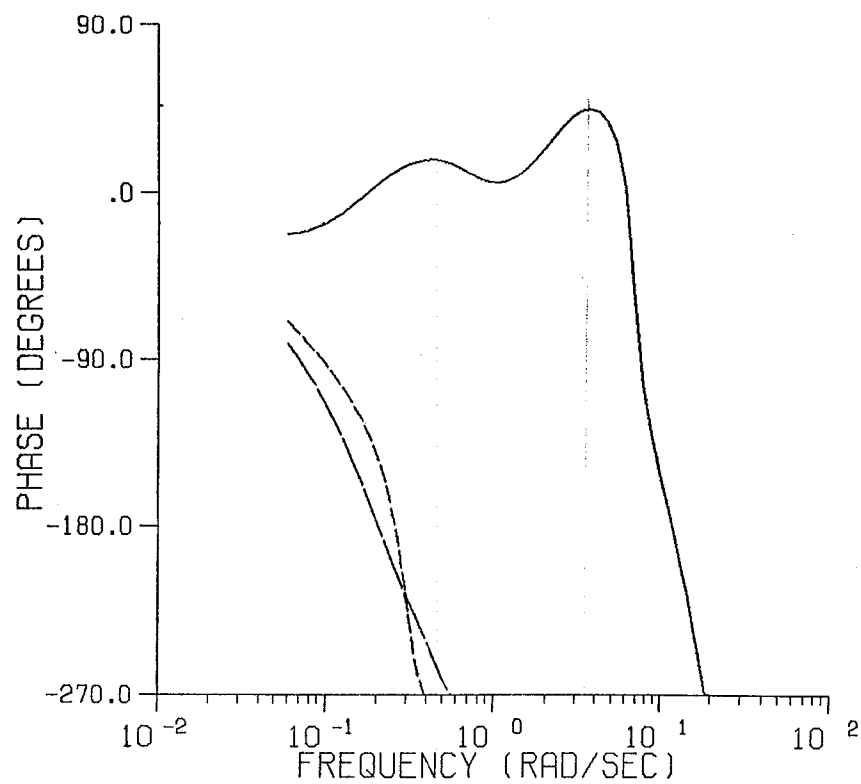
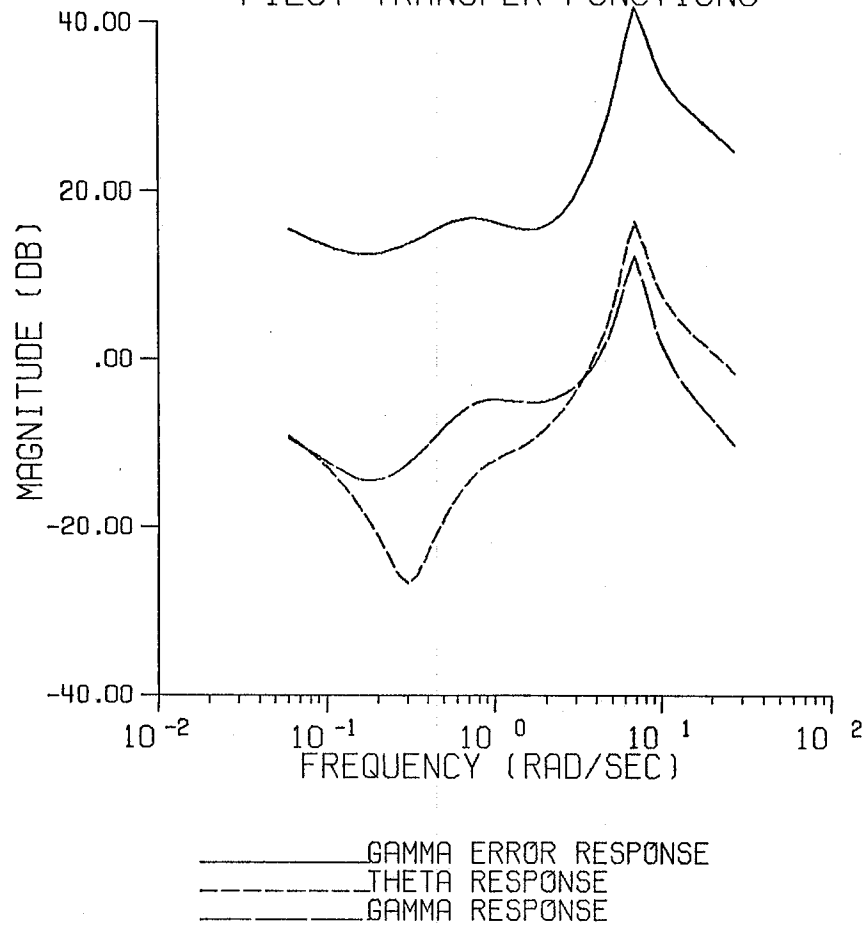


—— GAMMA ERROR RESPONSE
- - - THETA RESPONSE
- . - GAMMA RESPONSE



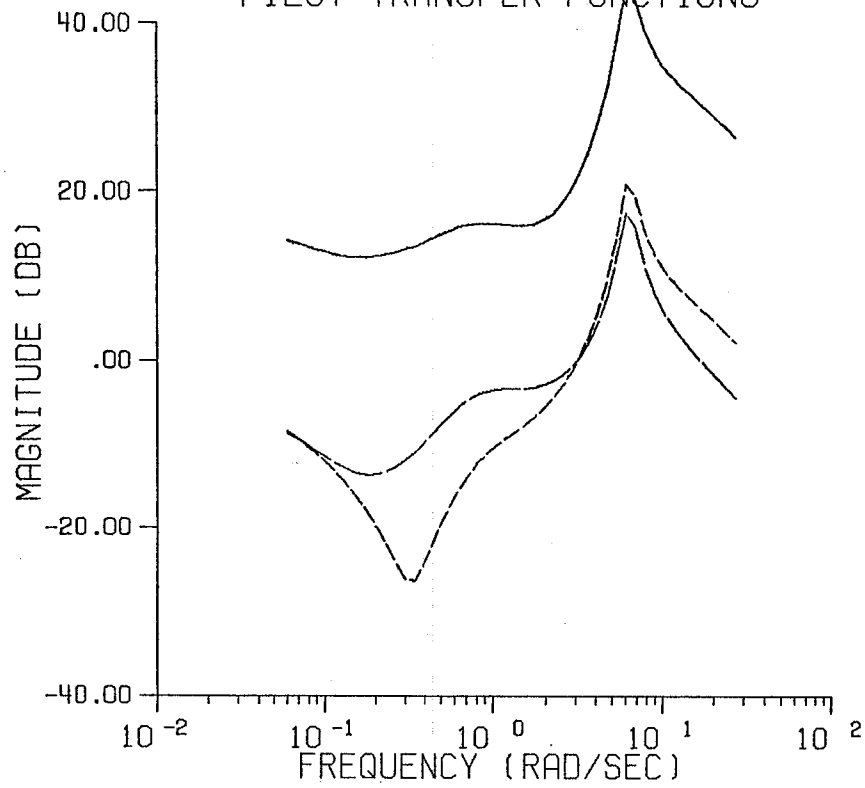
CONFIGURATION 2-2 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS

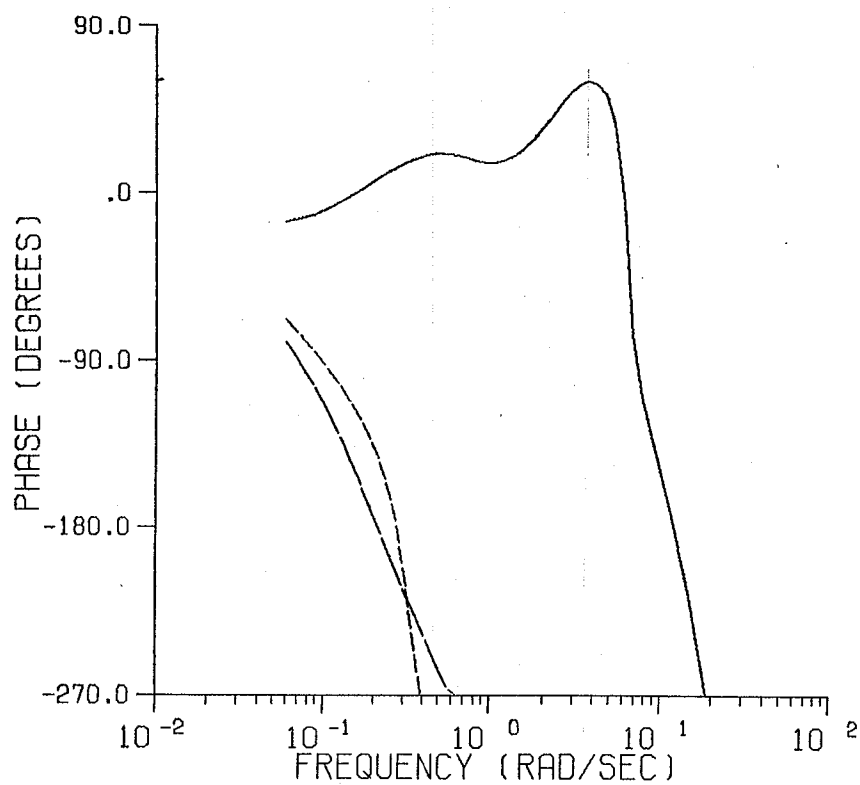


CONFIGURATION 2-3 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS

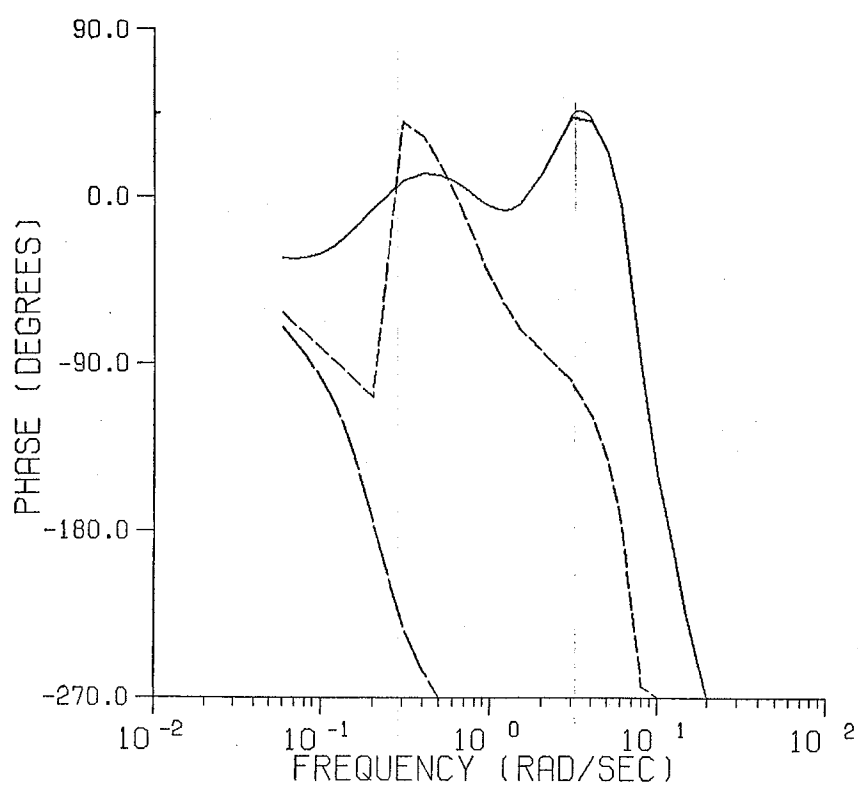
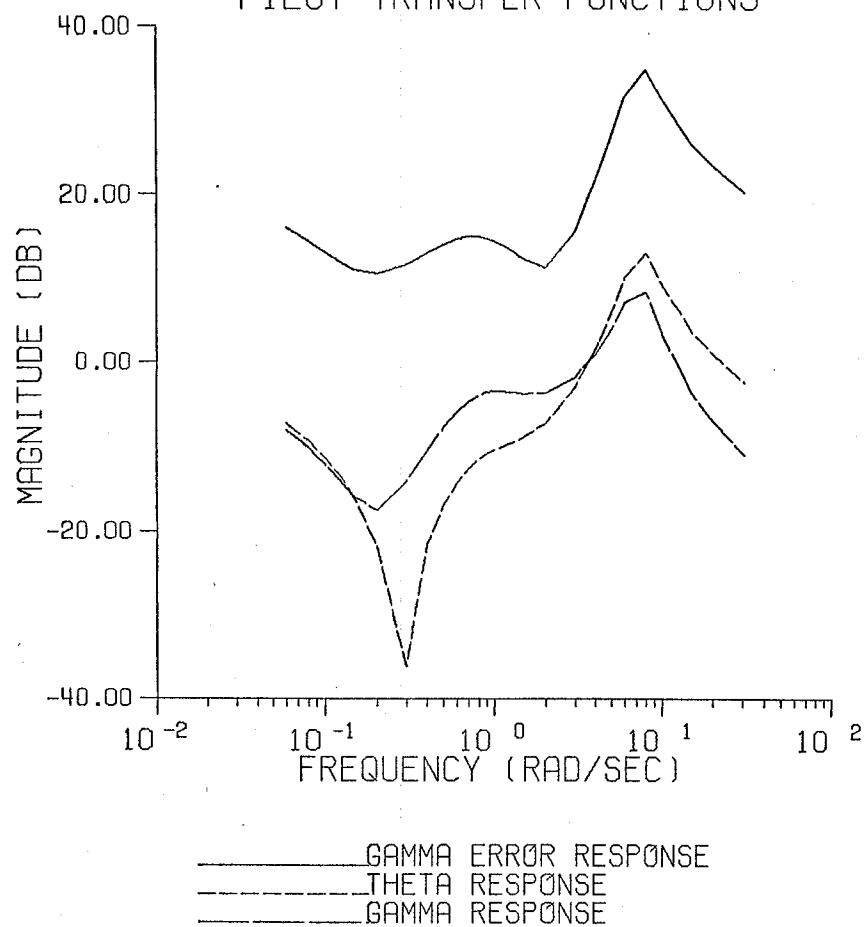


—— GAMMA ERROR RESPONSE
----- THETA RESPONSE
- . - . GAMMA RESPONSE



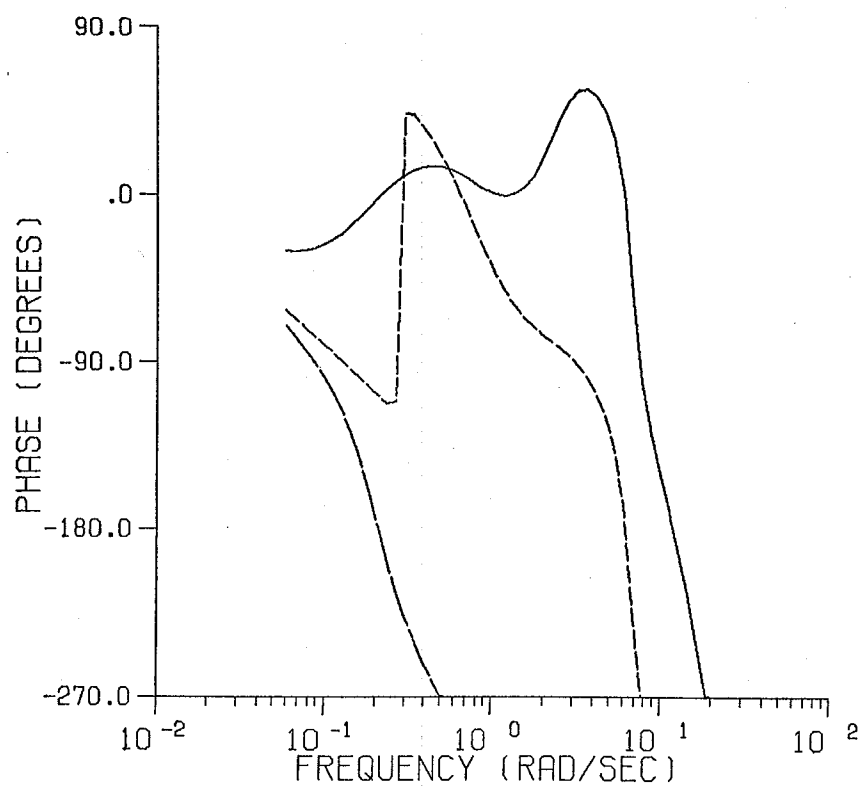
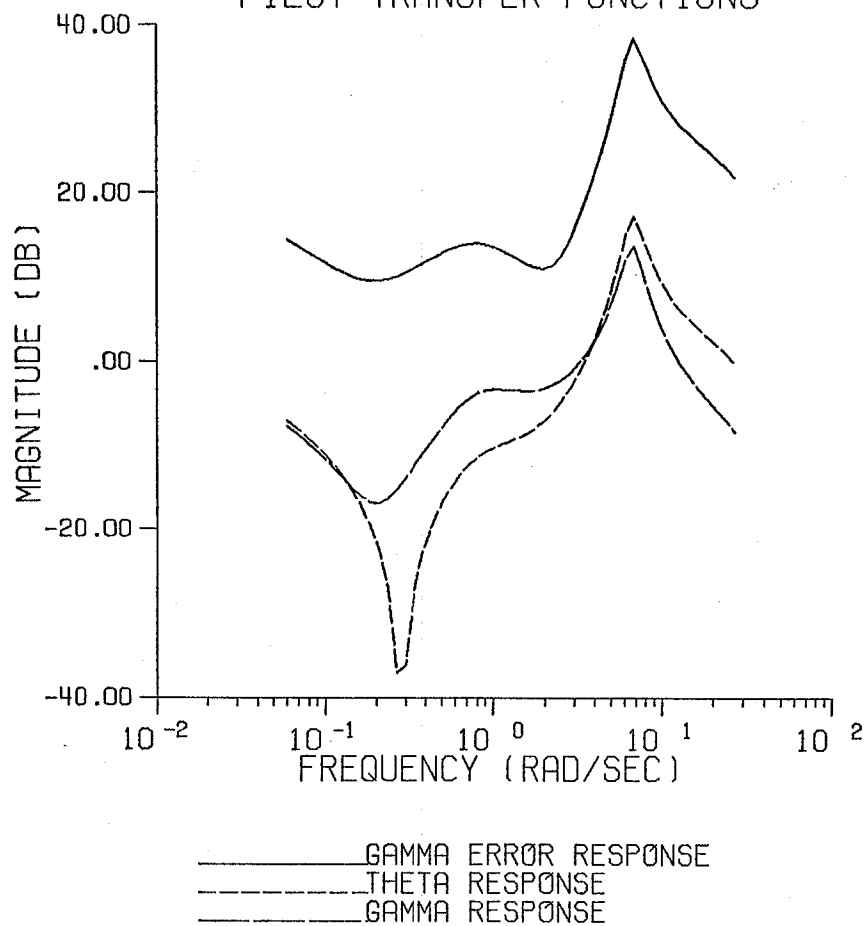
CONFIGURATION 3-1 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS

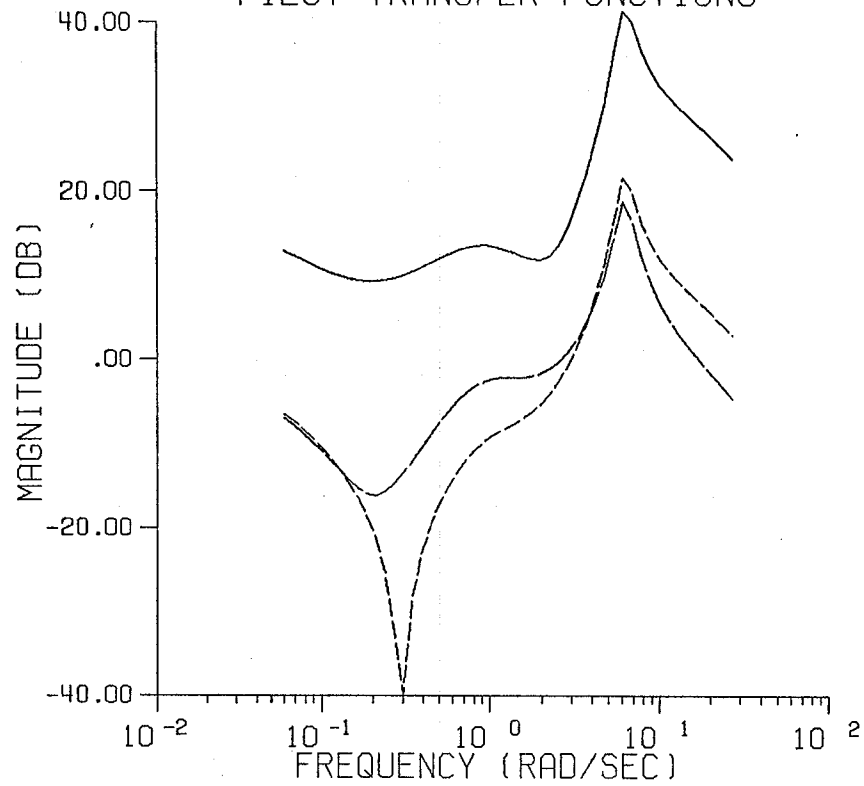


CONFIGURATION 3-2 GAMMA TRACKING

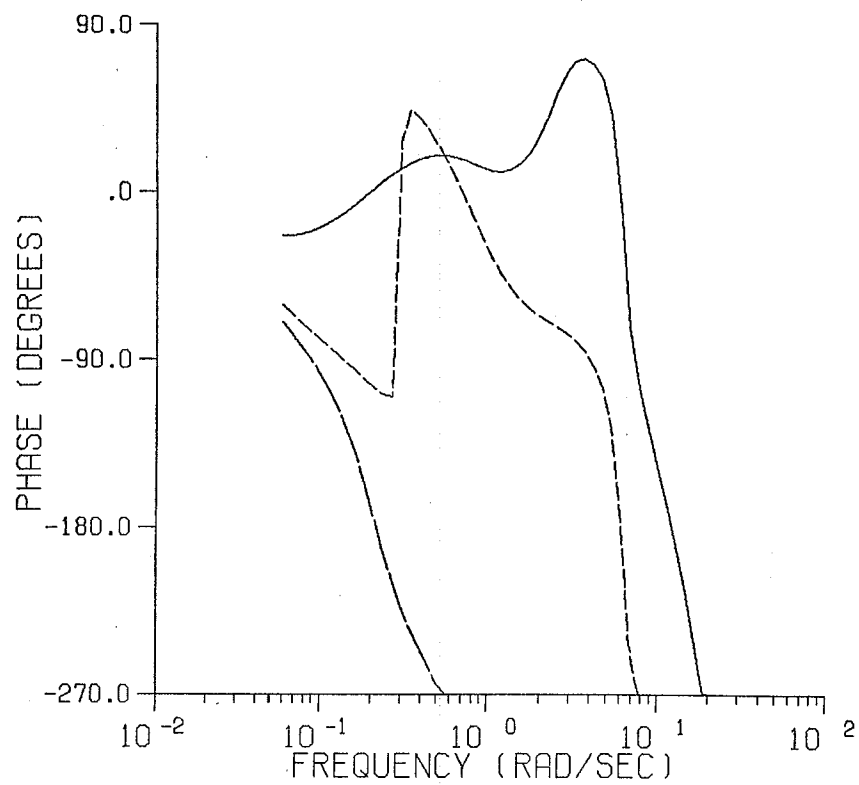
PILOT TRANSFER FUNCTIONS



CONFIGURATION 3-3 GAMMA TRACKING
PILOT TRANSFER FUNCTIONS

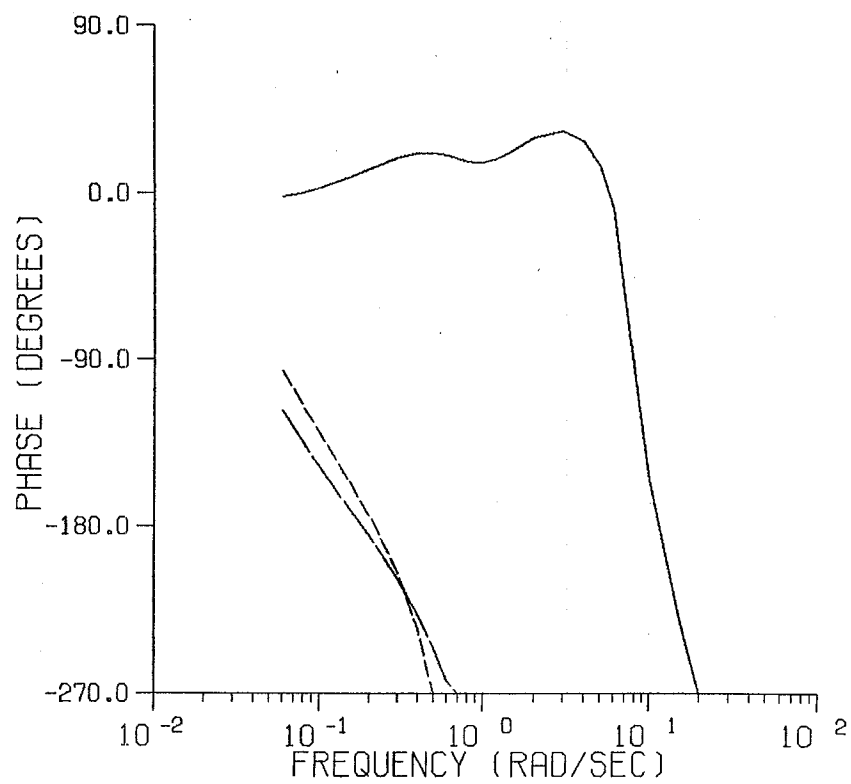
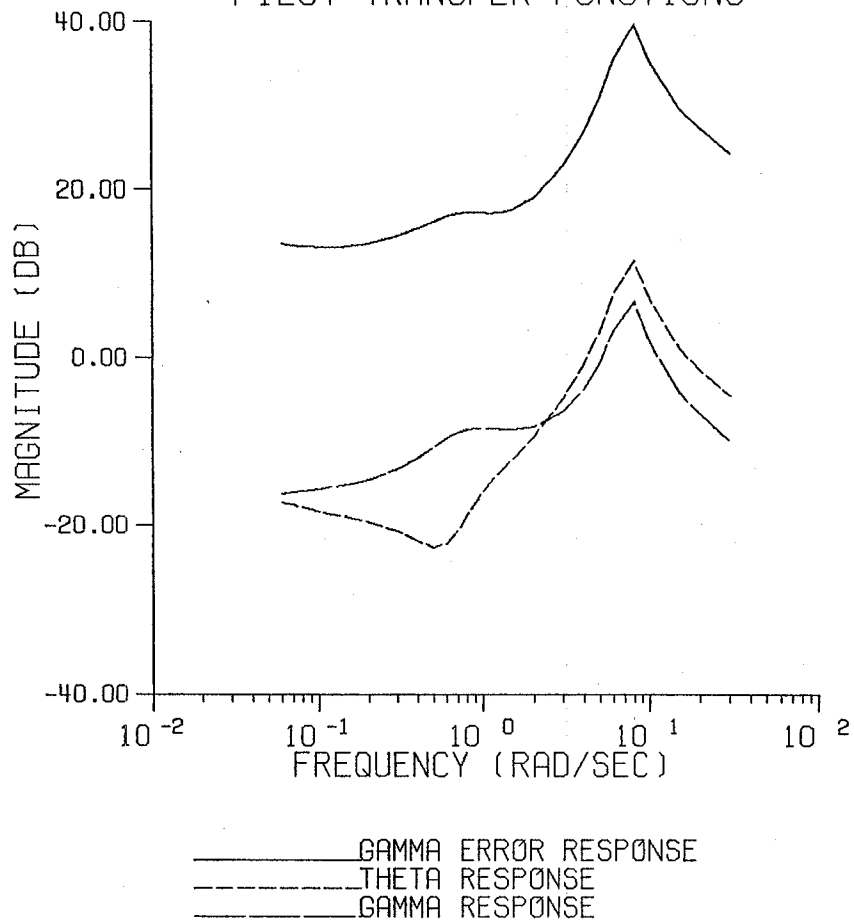


— GAMMA ERROR RESPONSE
- - - THETA RESPONSE
- . - GAMMA RESPONSE



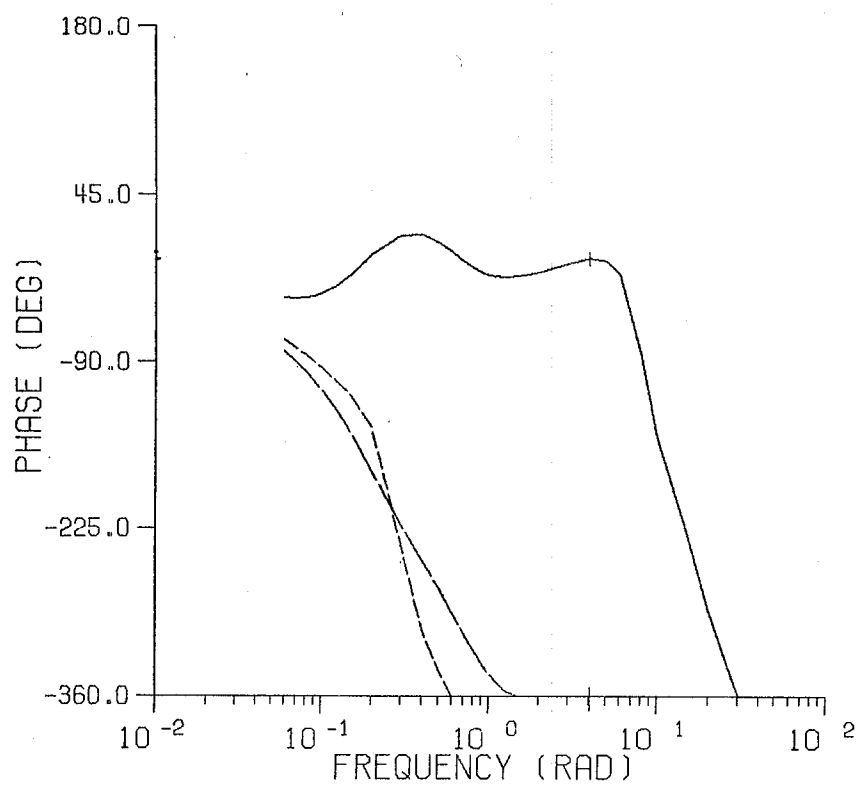
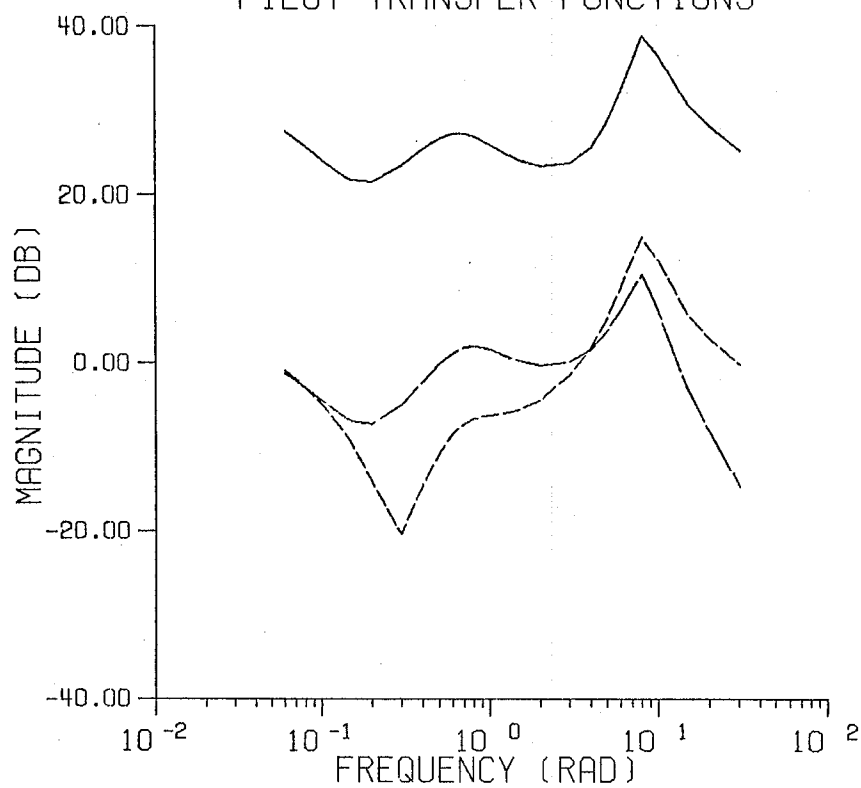
CONFIGURATION 4-1 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS



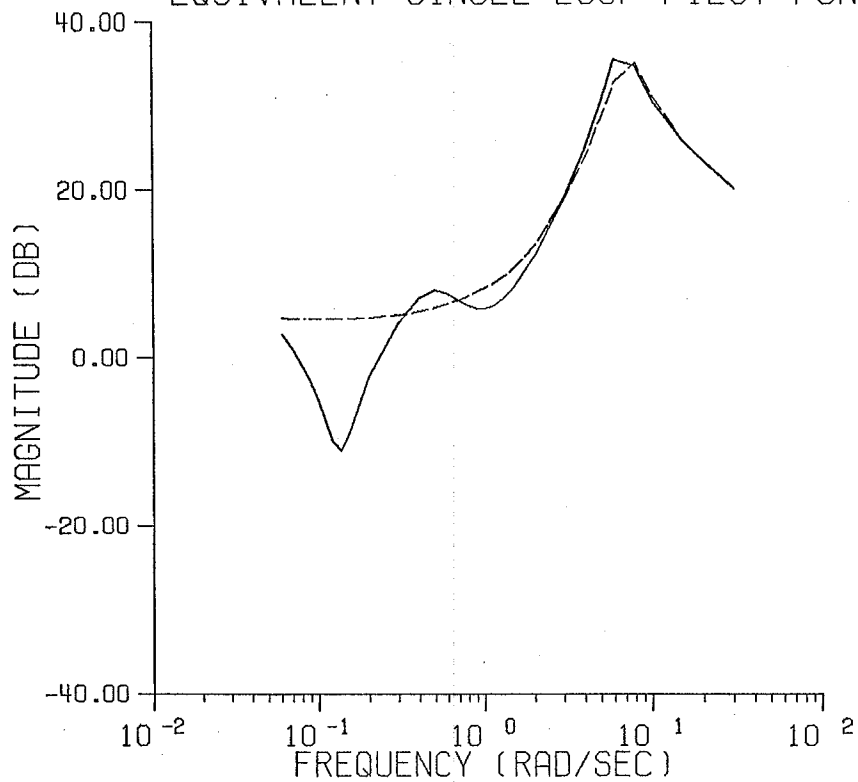
CONFIGURATION 5-1 GAMMA TRACKING

PILOT TRANSFER FUNCTIONS

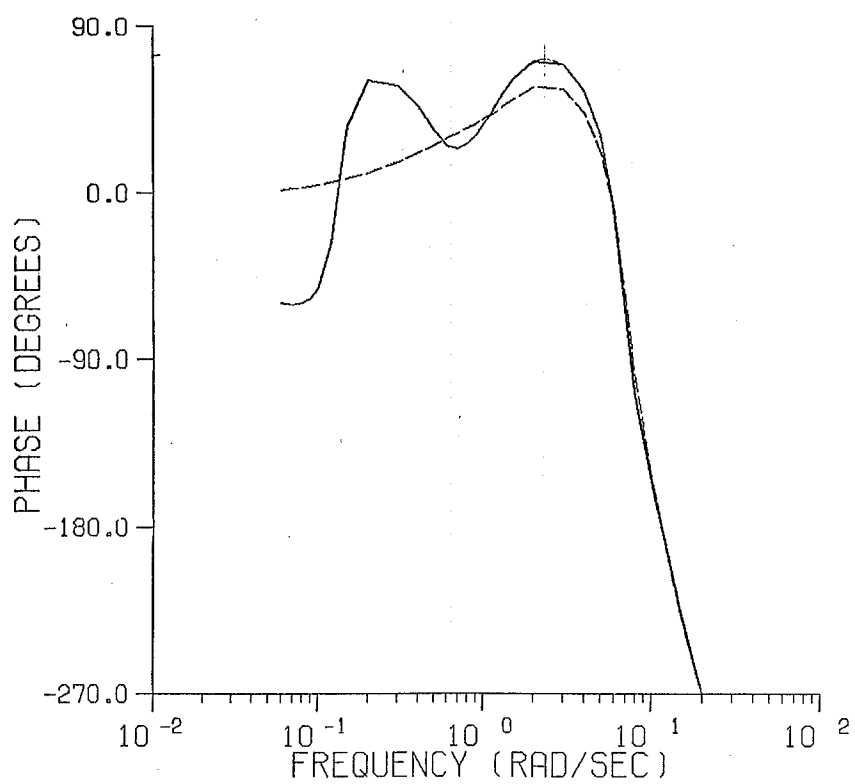


CONFIGURATION 1-1 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

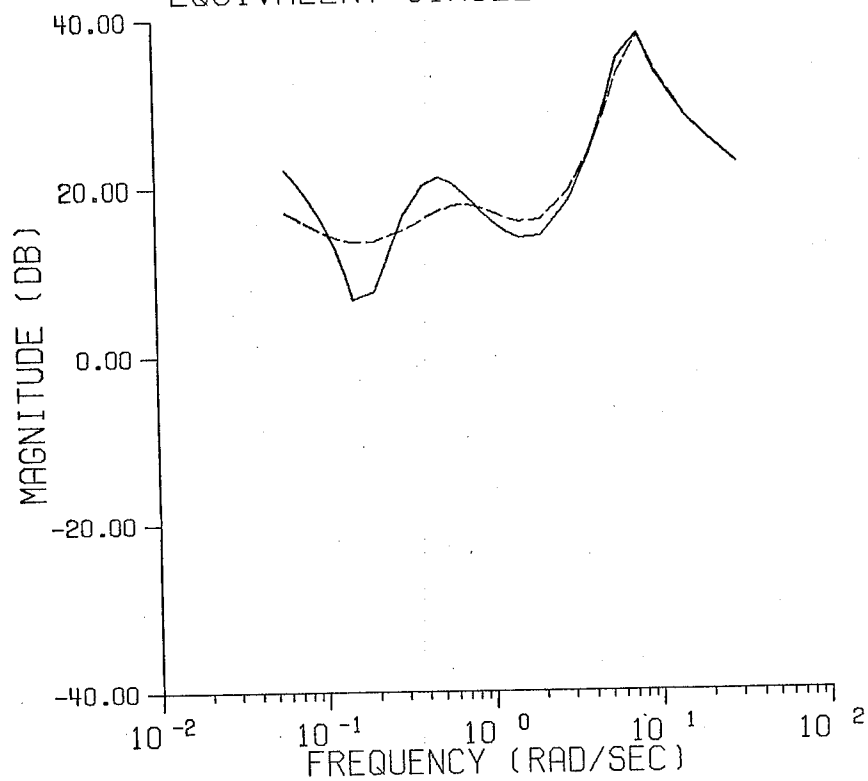


—— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

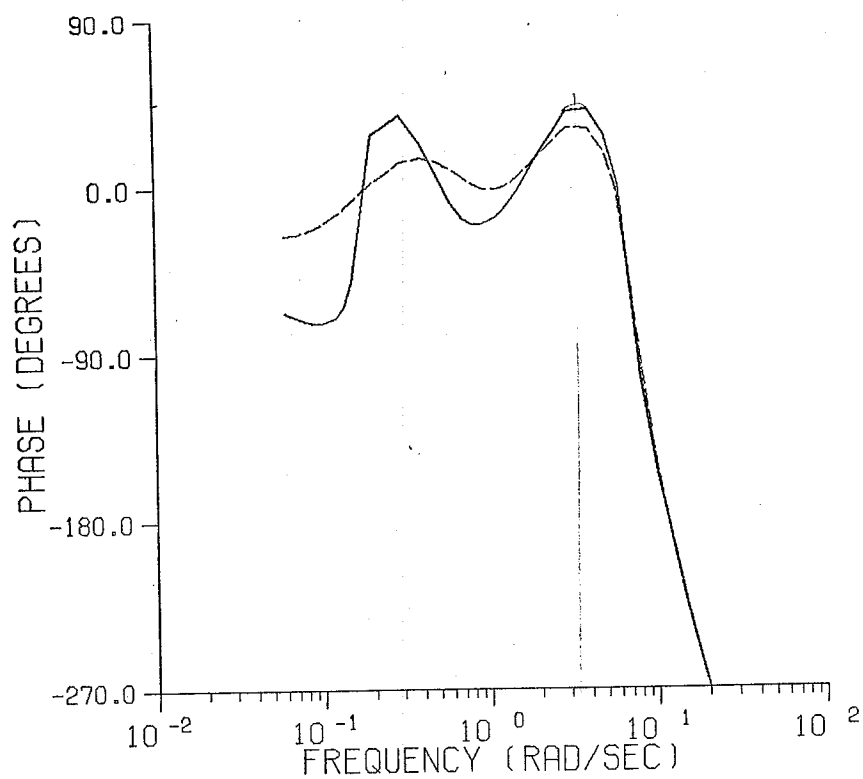


CONFIGURATION 2-1 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

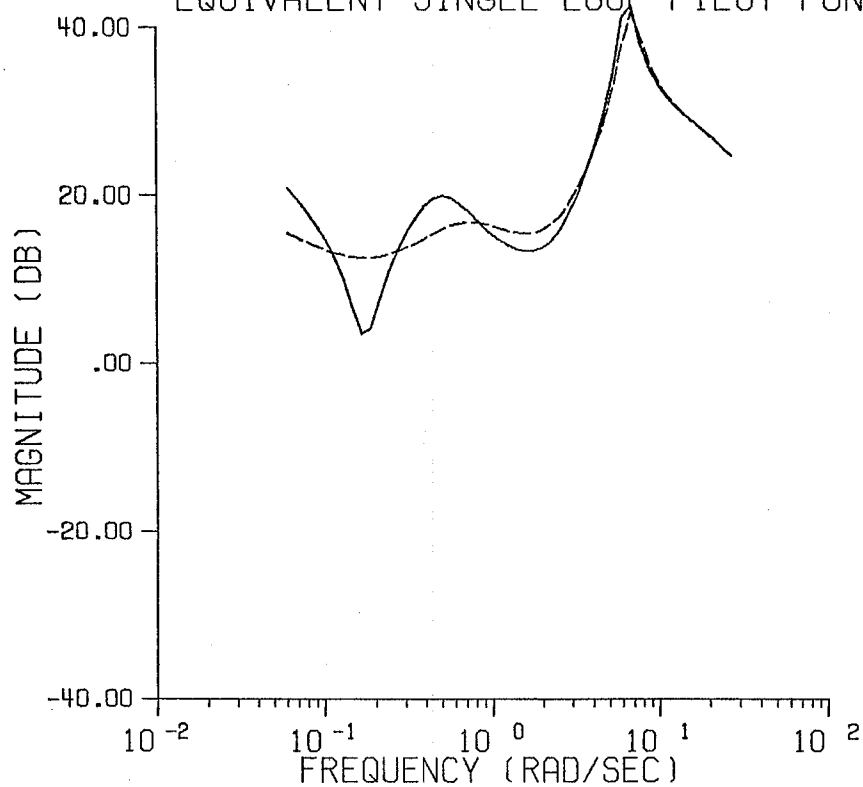


———— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

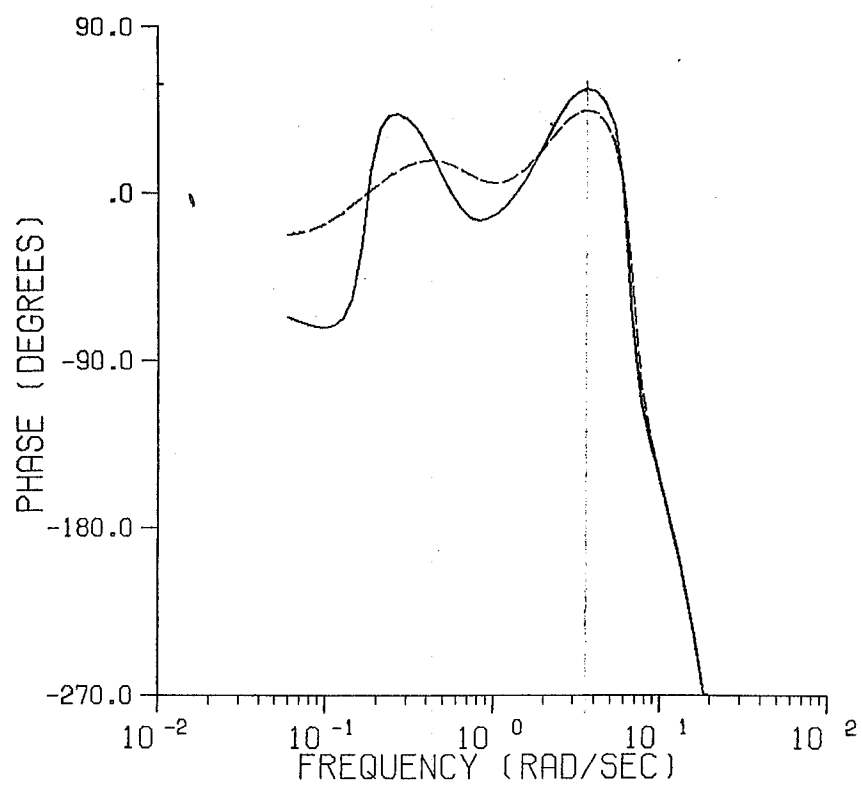


CONFIGURATION 2-2 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

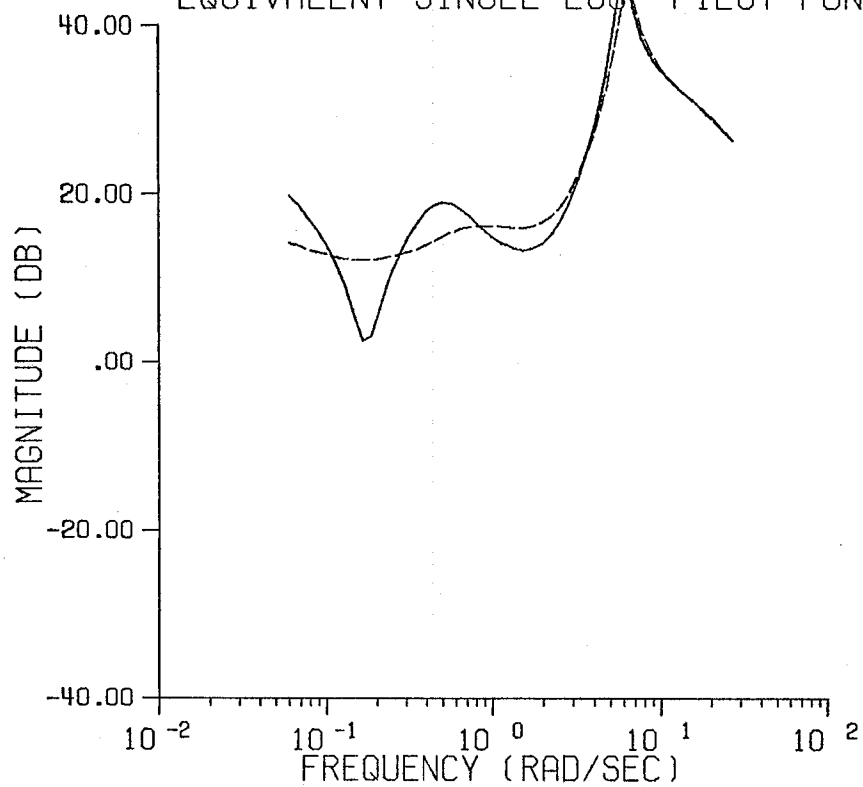


—— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

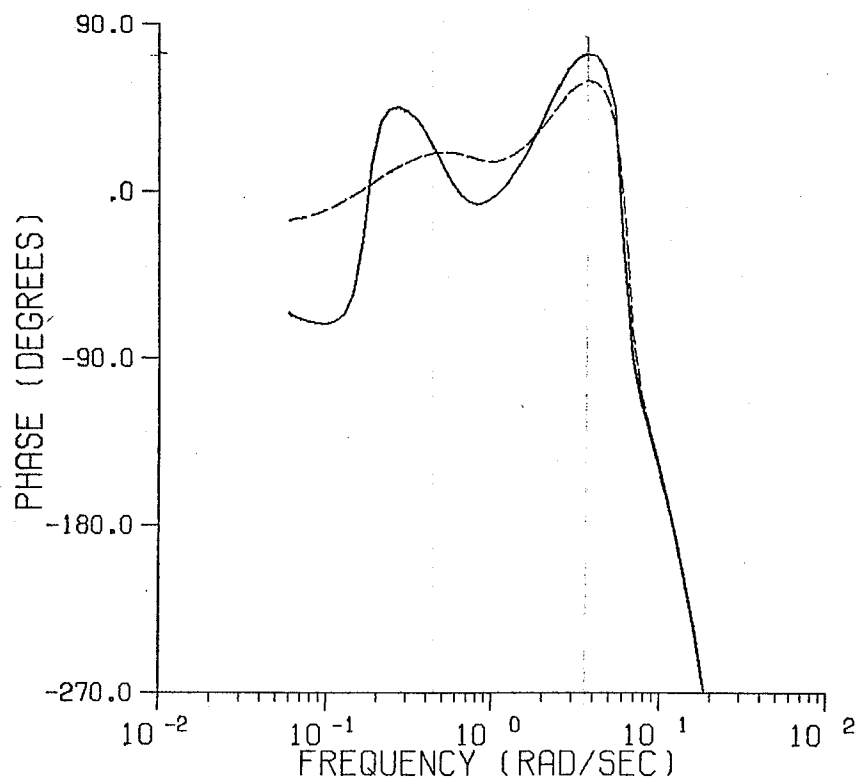


CONFIGURATION 2-3 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

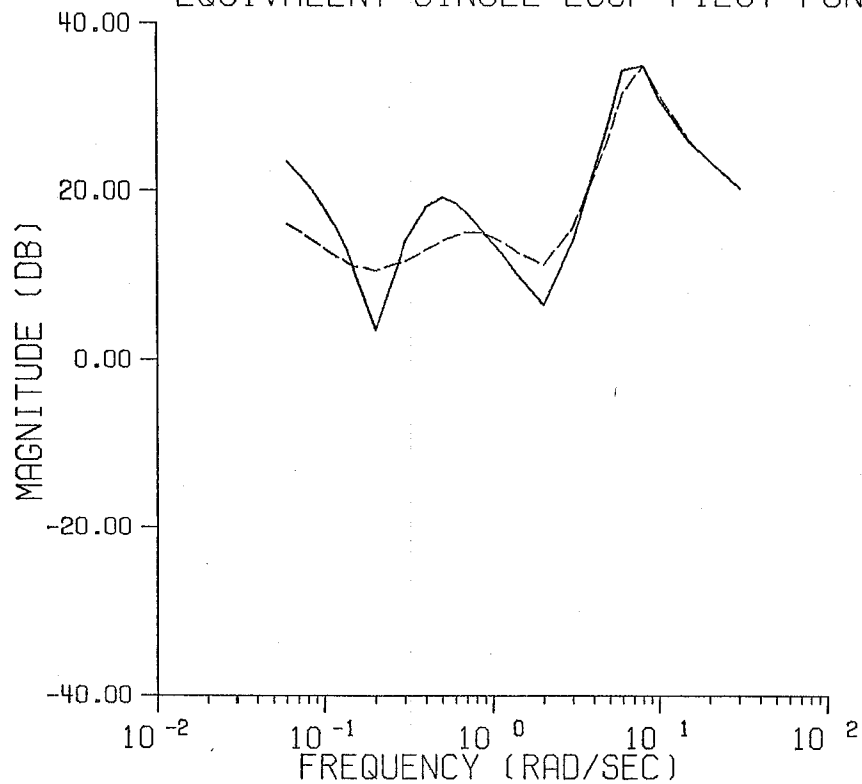


———— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

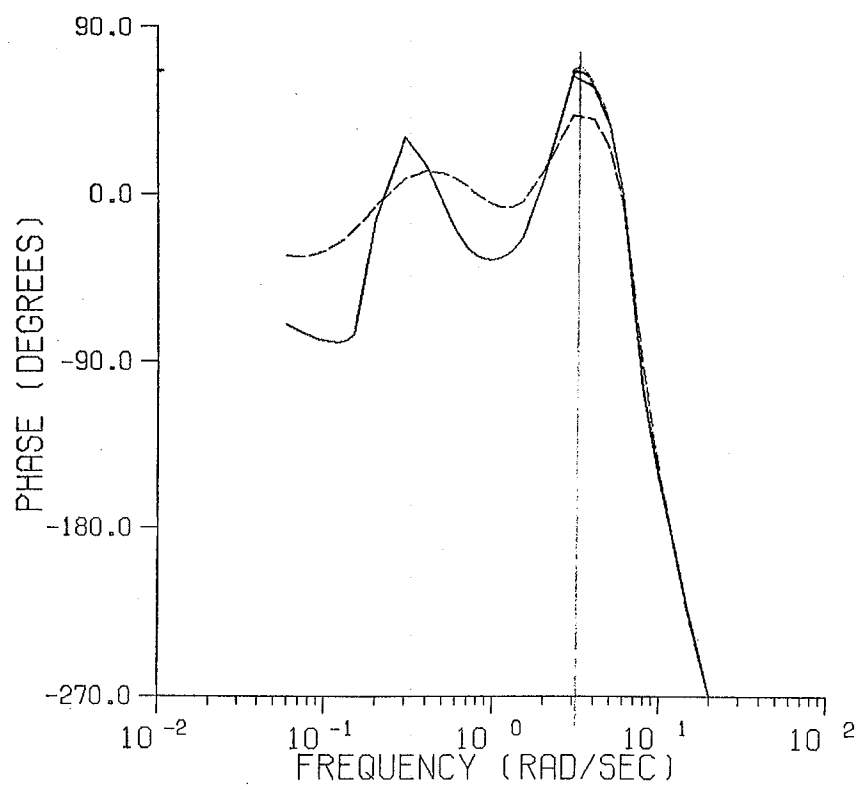


CONFIGURATION 3-1 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

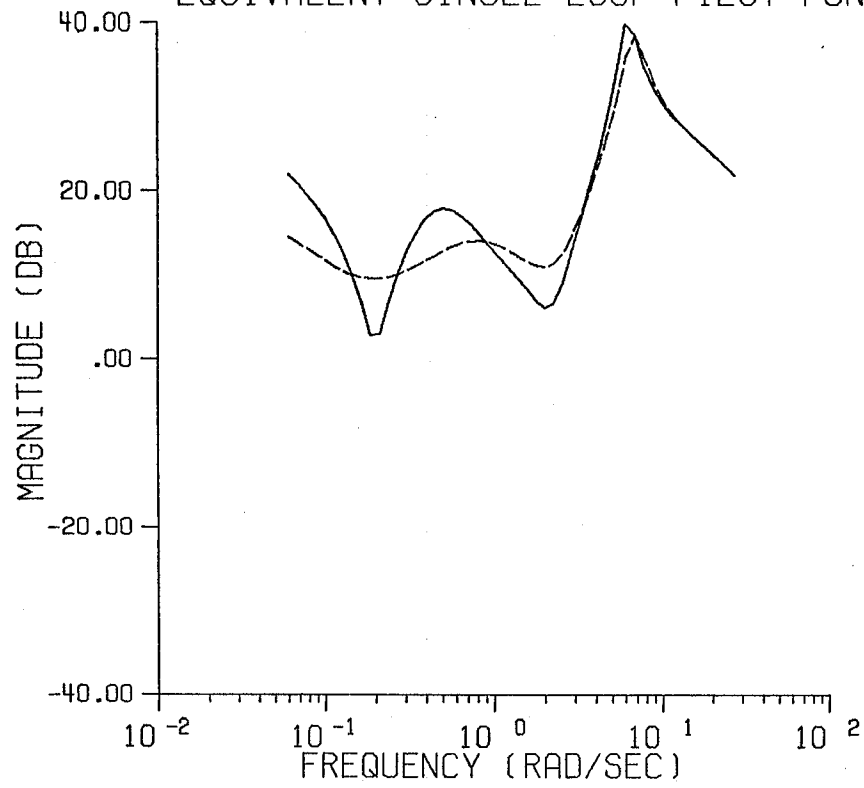


—— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

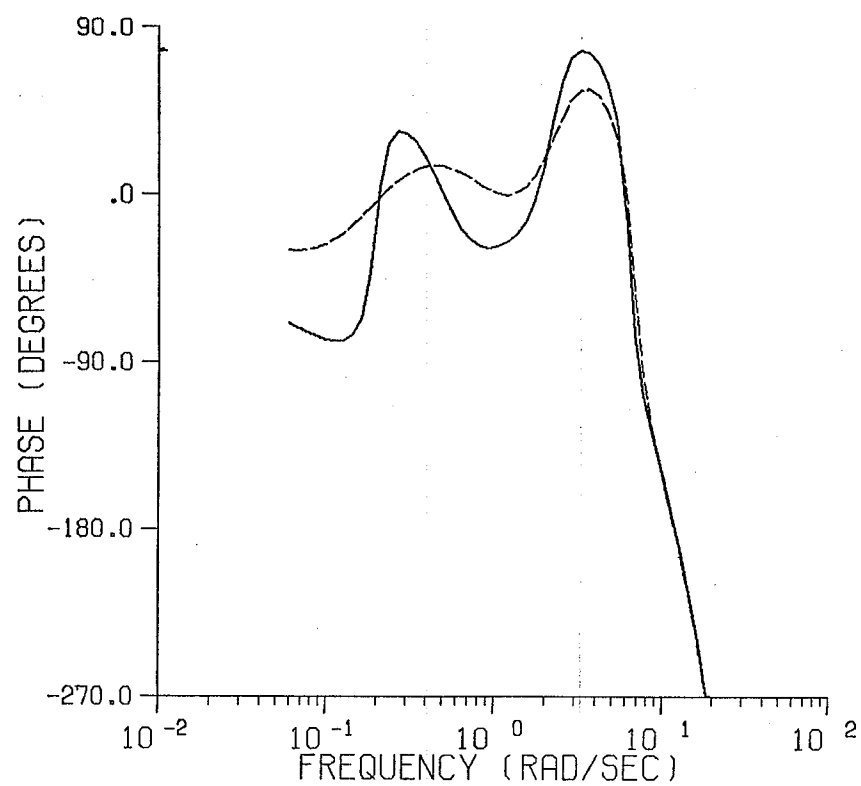


CONFIGURATION 3-2 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

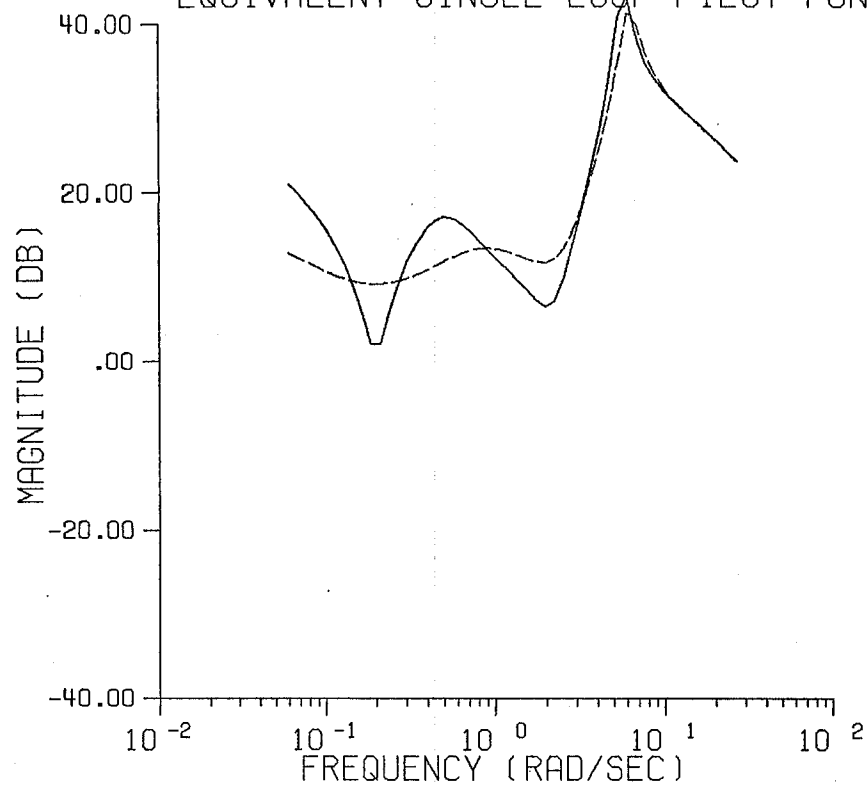


————— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

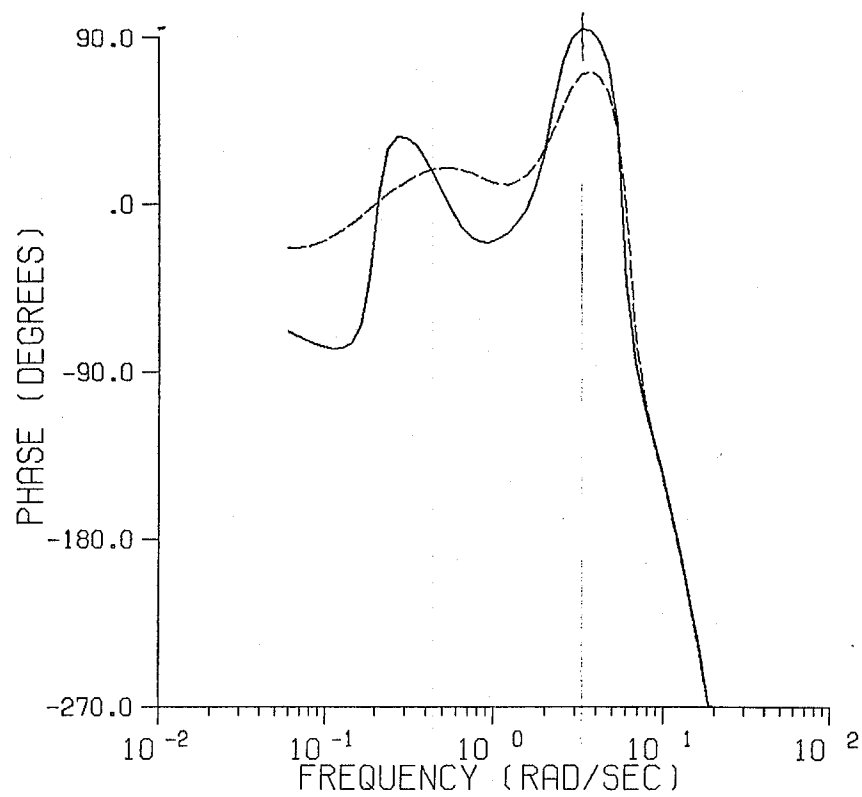


CONFIGURATION 3-3 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

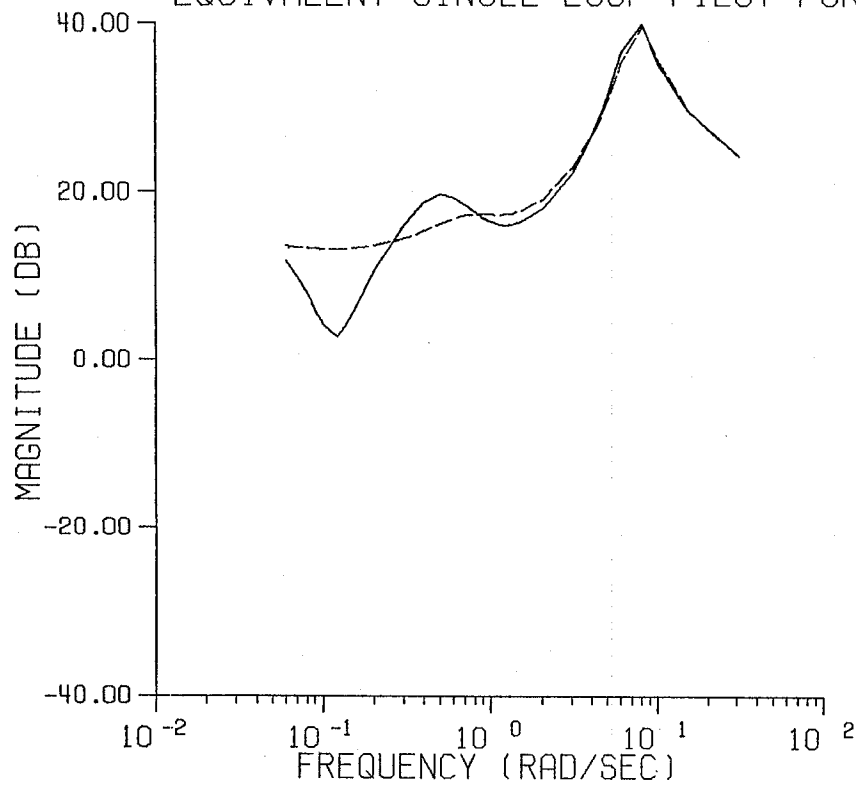


—— EQUIVALENT SINGLE PILOT FUNCTION
----- GAMMA ERROR RESPONSE

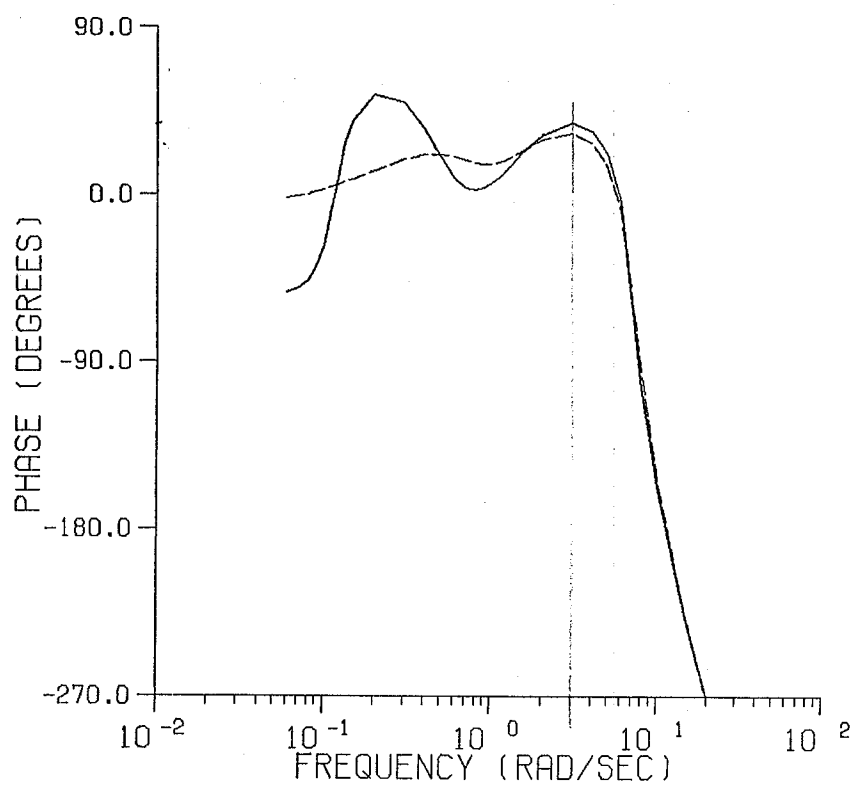


CONFIGURATION 4-1 GAMMA TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

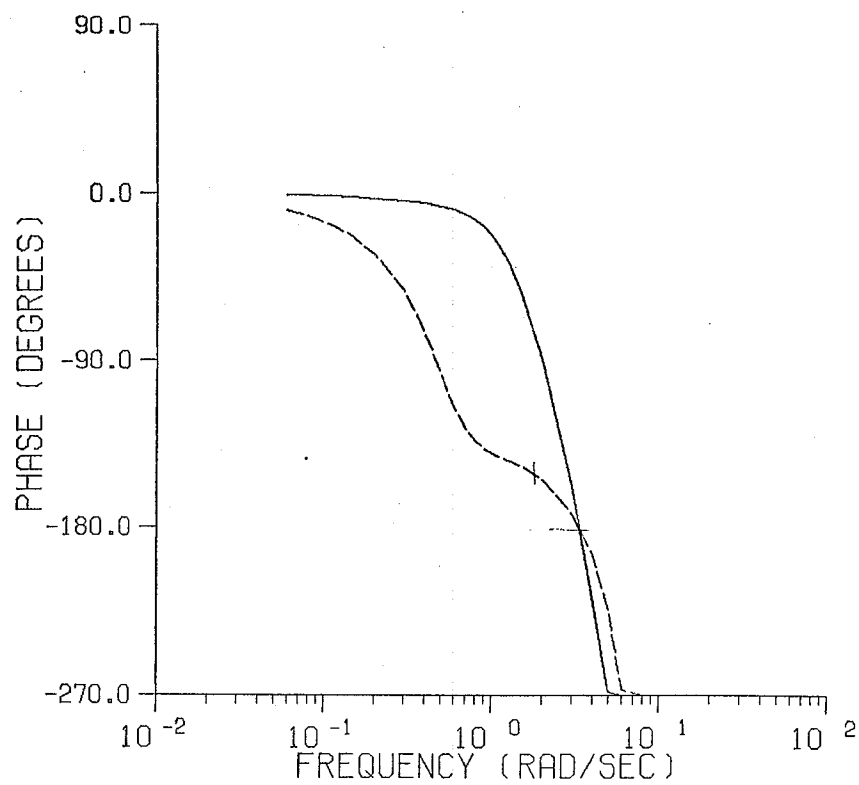
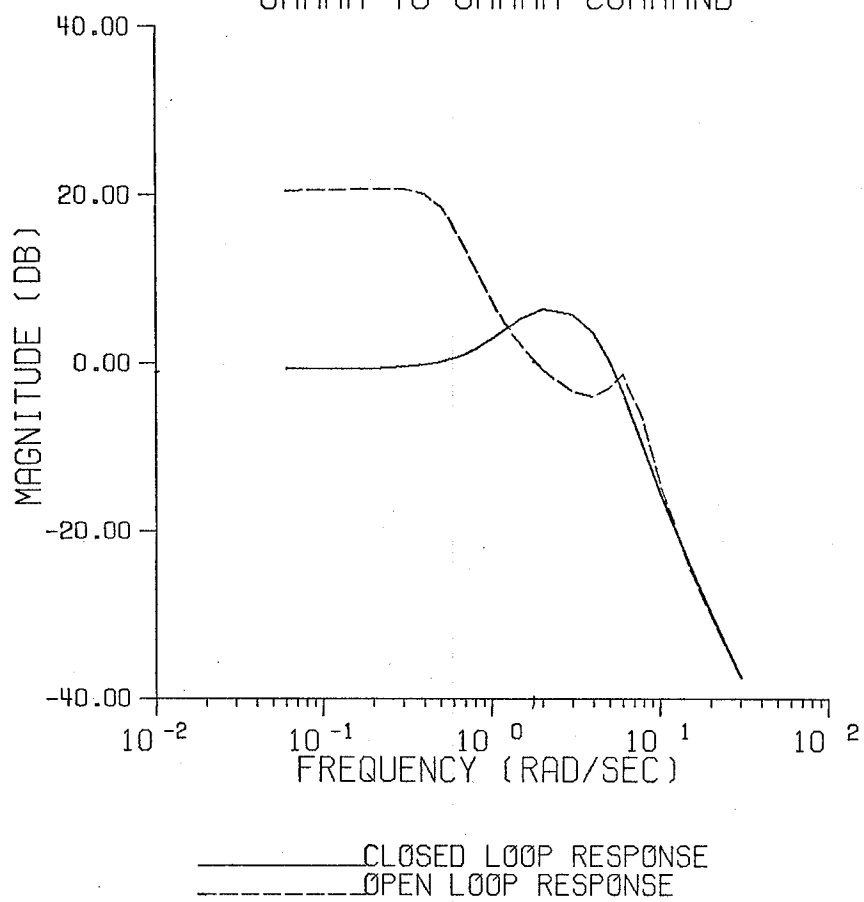


—— EQUIVALENT SINGLE PILOT FUNCTION
- - - GAMMA ERROR RESPONSE



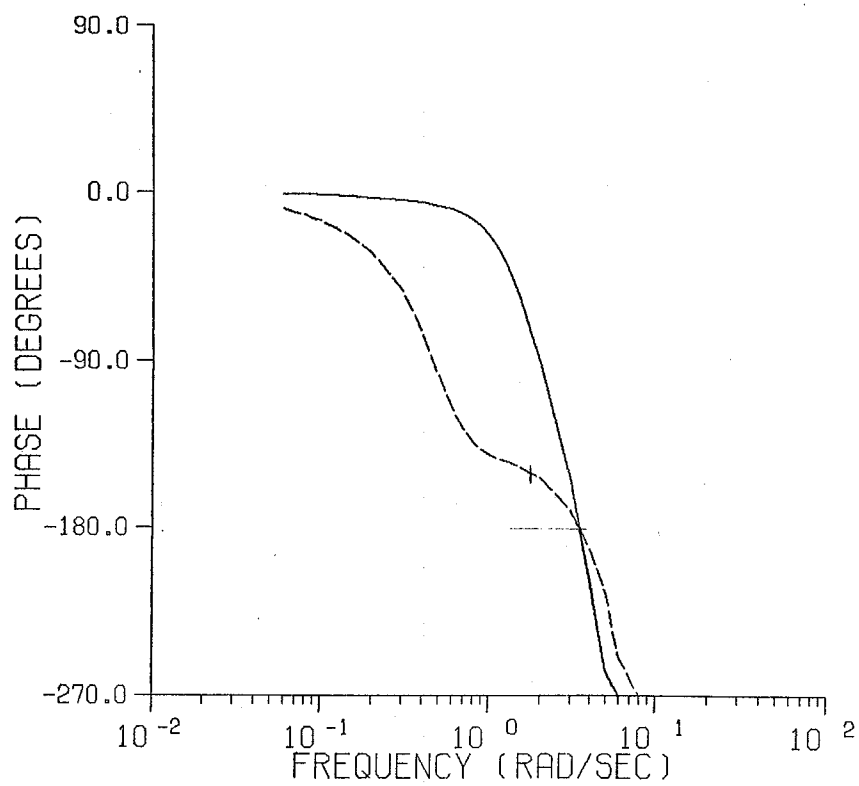
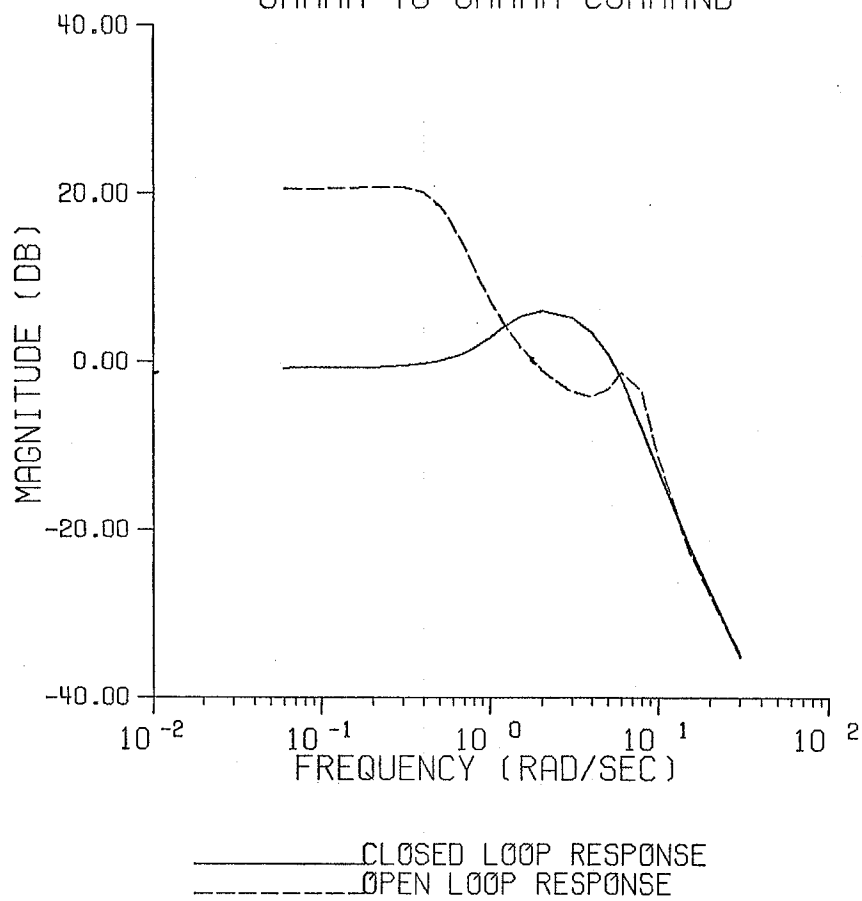
CONFIGURATION 1-1 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



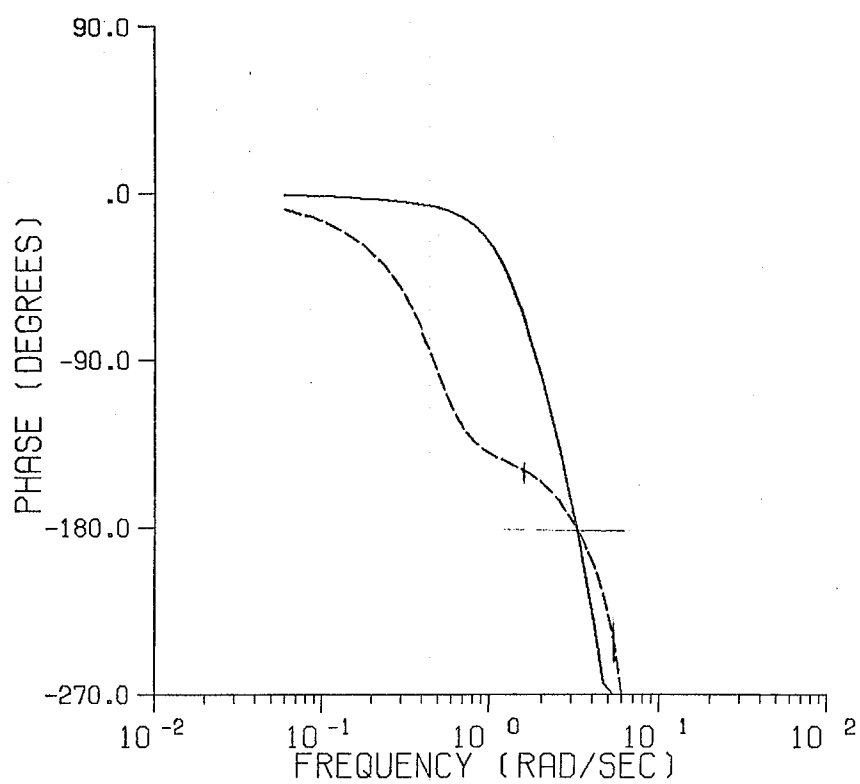
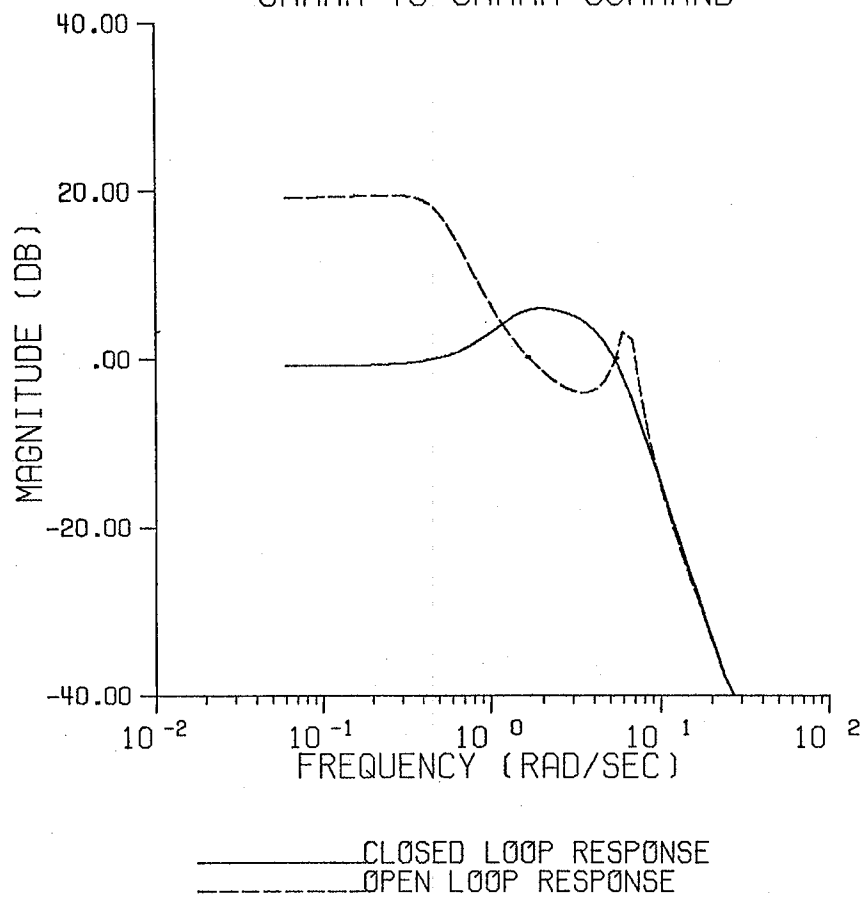
CONFIGURATION 2-1 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



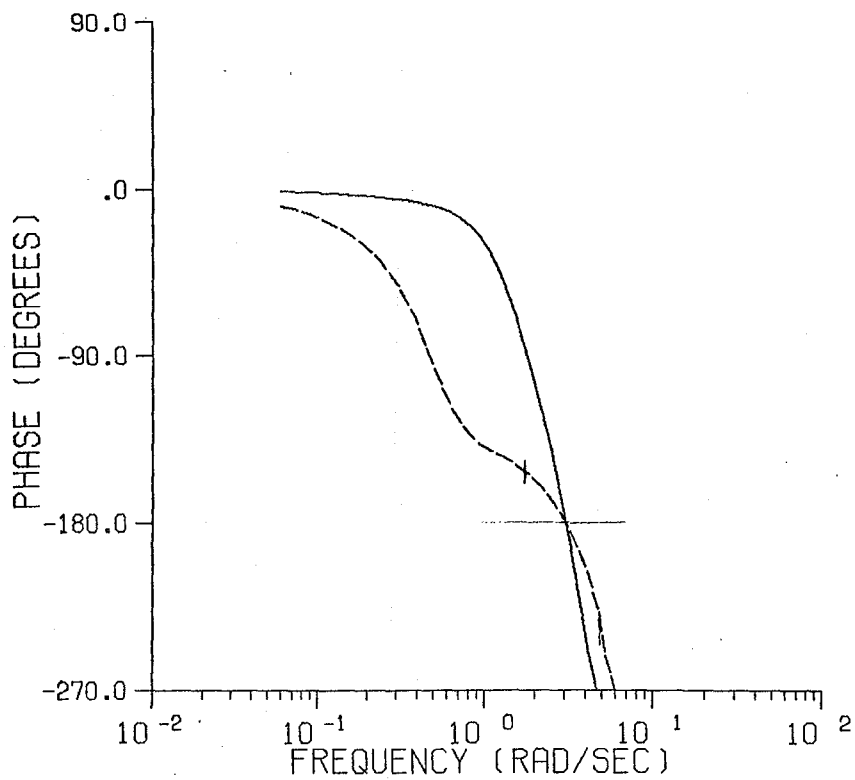
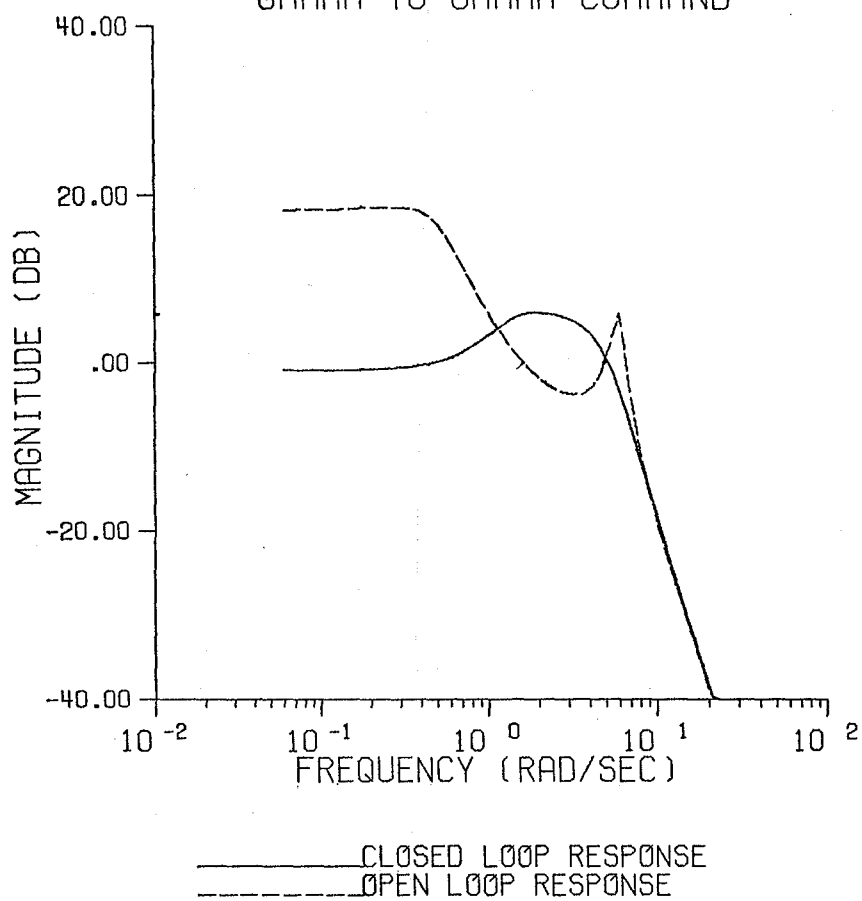
CONFIGURATION 2-2 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



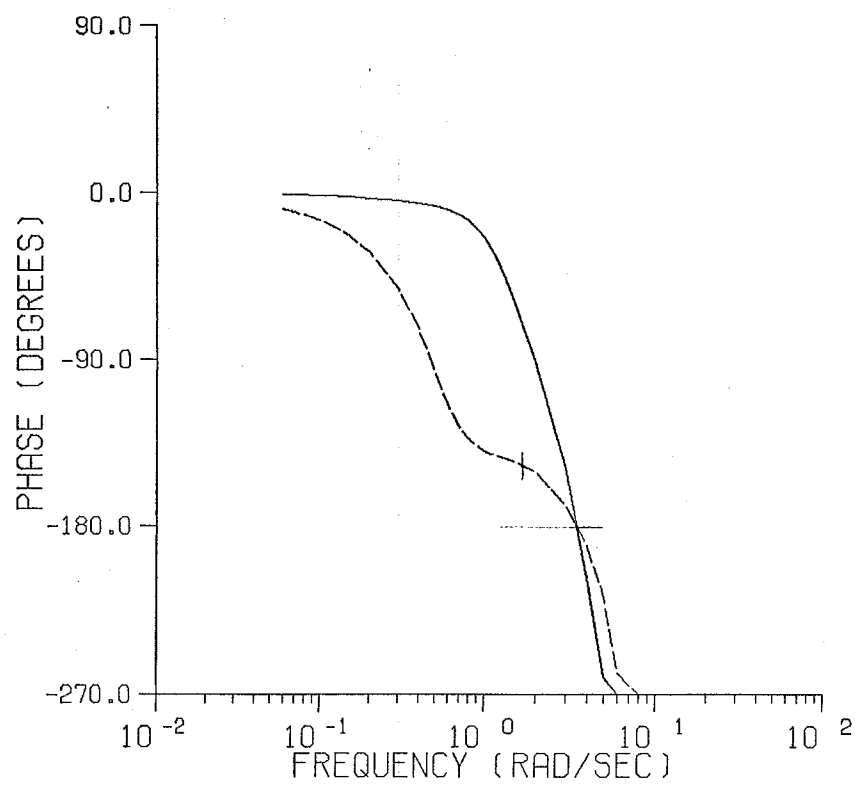
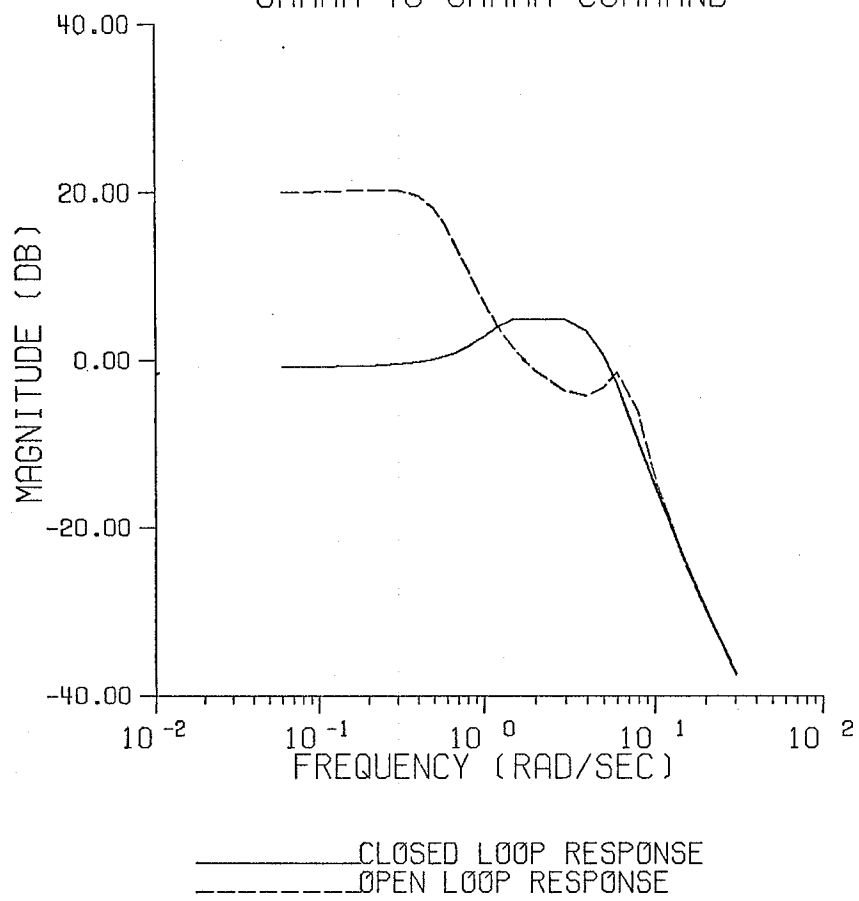
CONFIGURATION 2-3 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



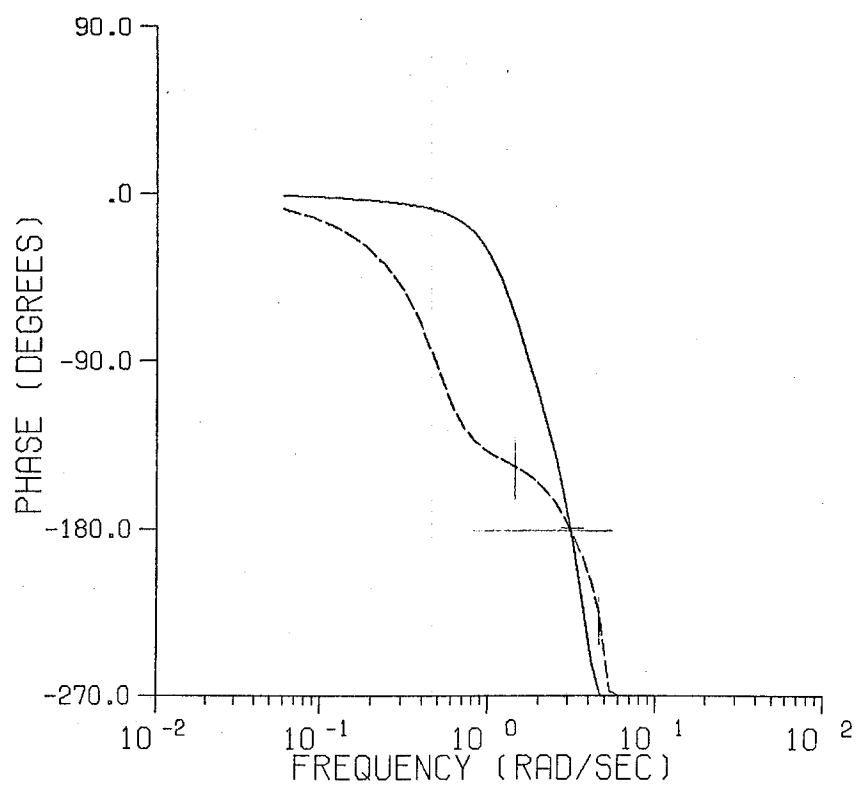
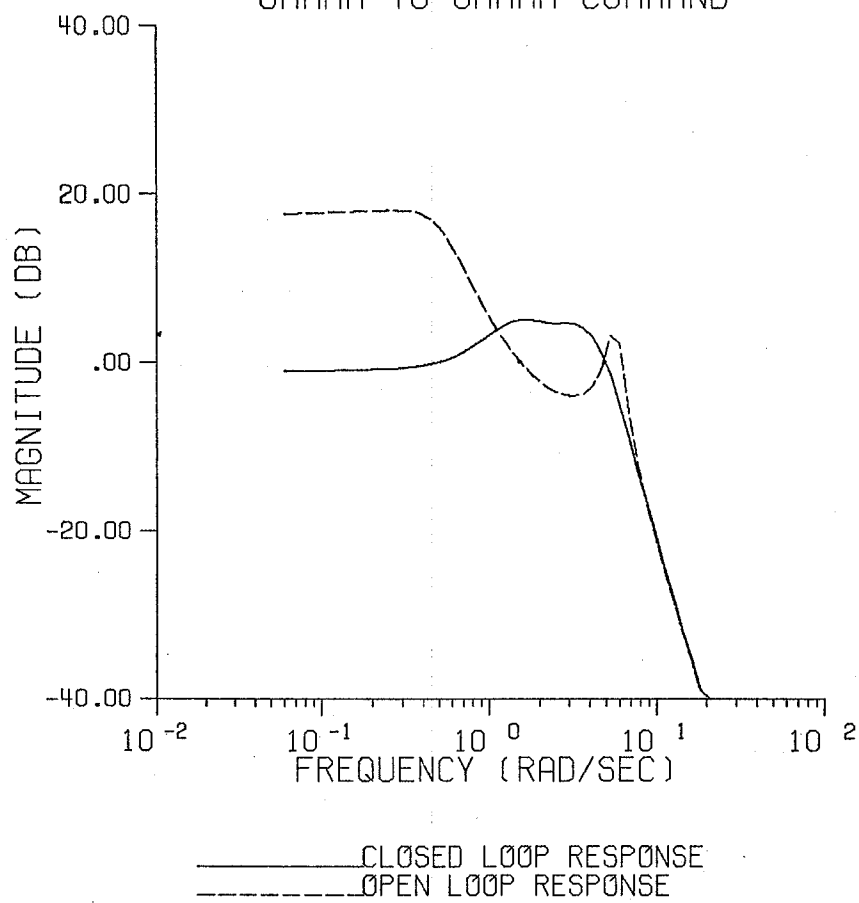
CONFIGURATION 3-1 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



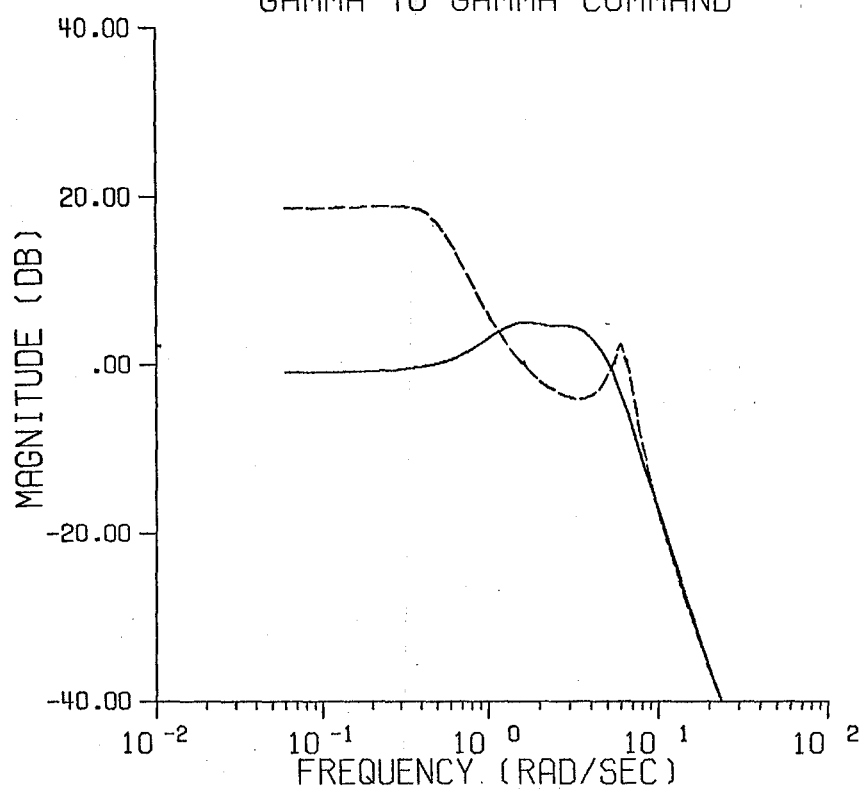
CONFIGURATION 3-3 GAMMA TRACKING

GAMMA TO GAMMA COMMAND

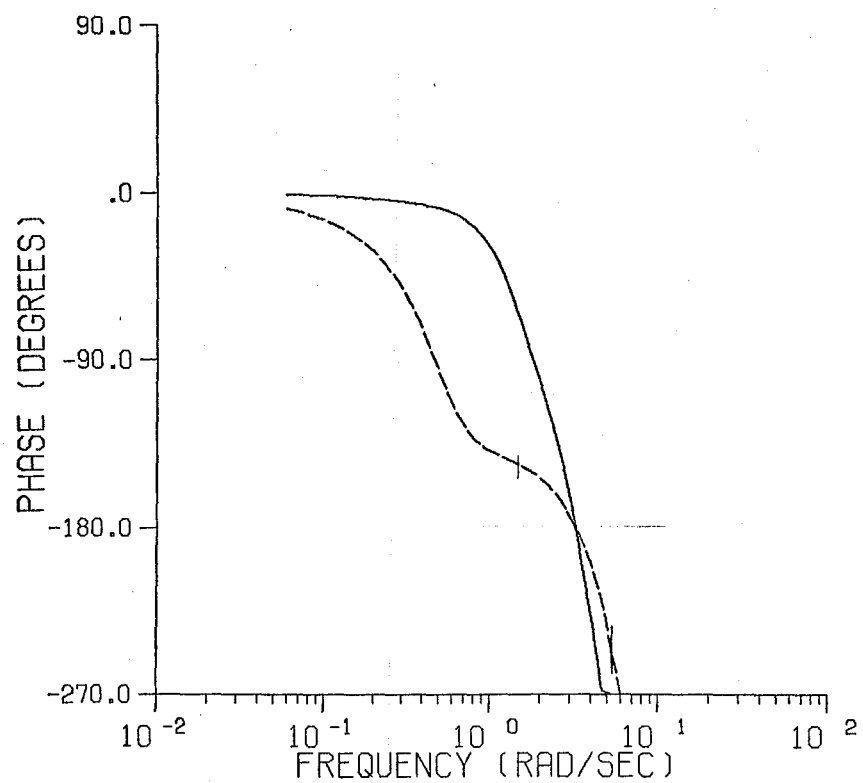


CONFIGURATION 3-2 GAMMA TRACKING

GAMMA TO GAMMA COMMAND

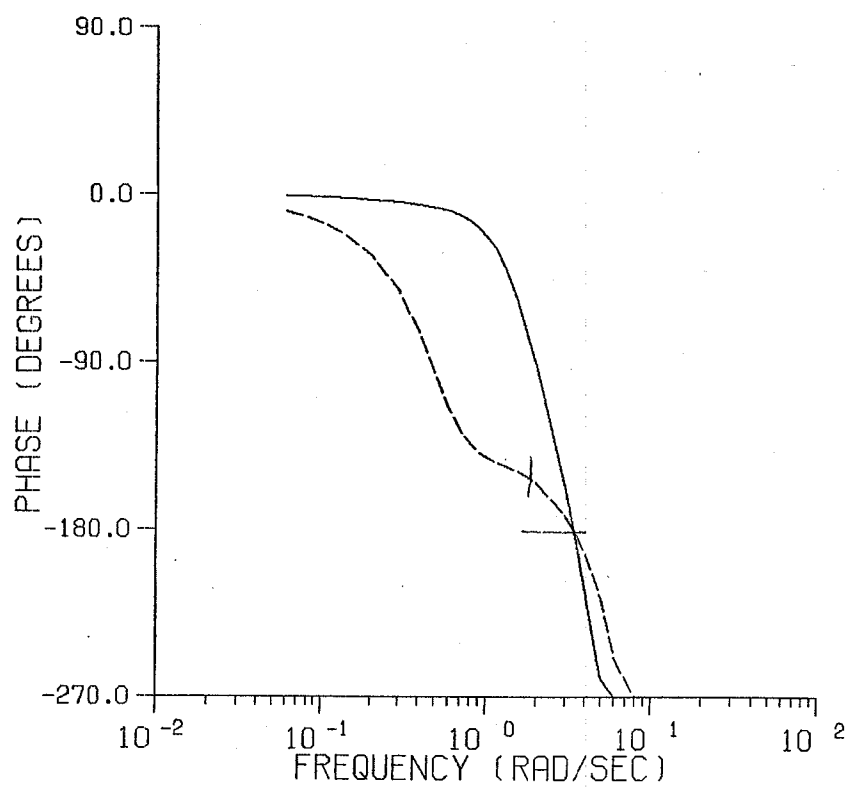
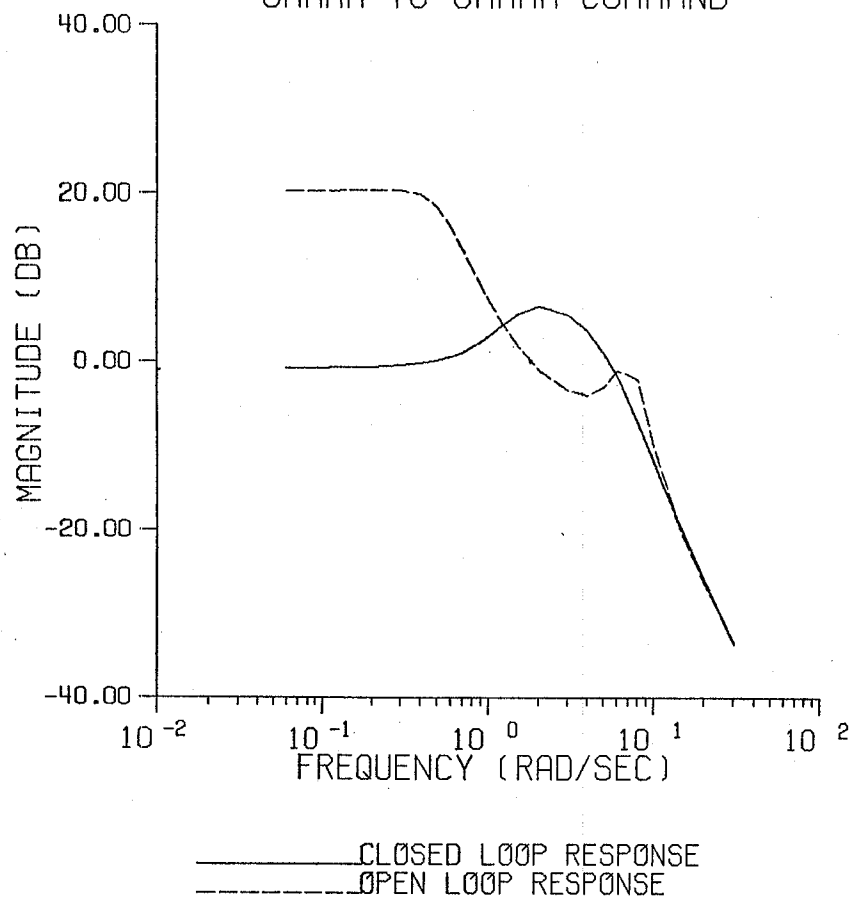


——— CLOSED LOOP RESPONSE
----- OPEN LOOP RESPONSE



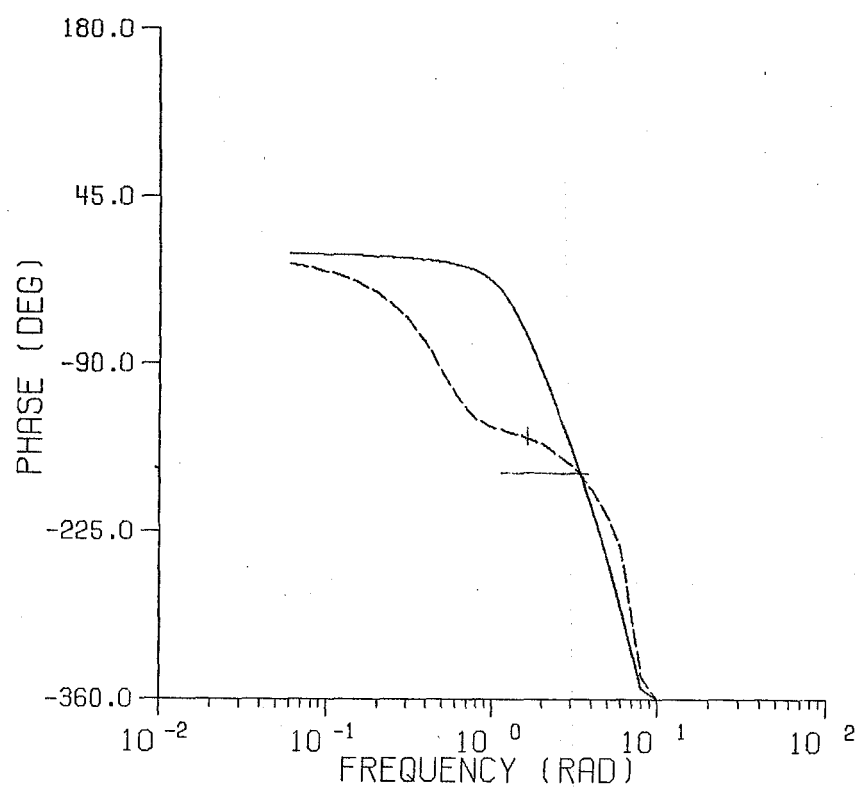
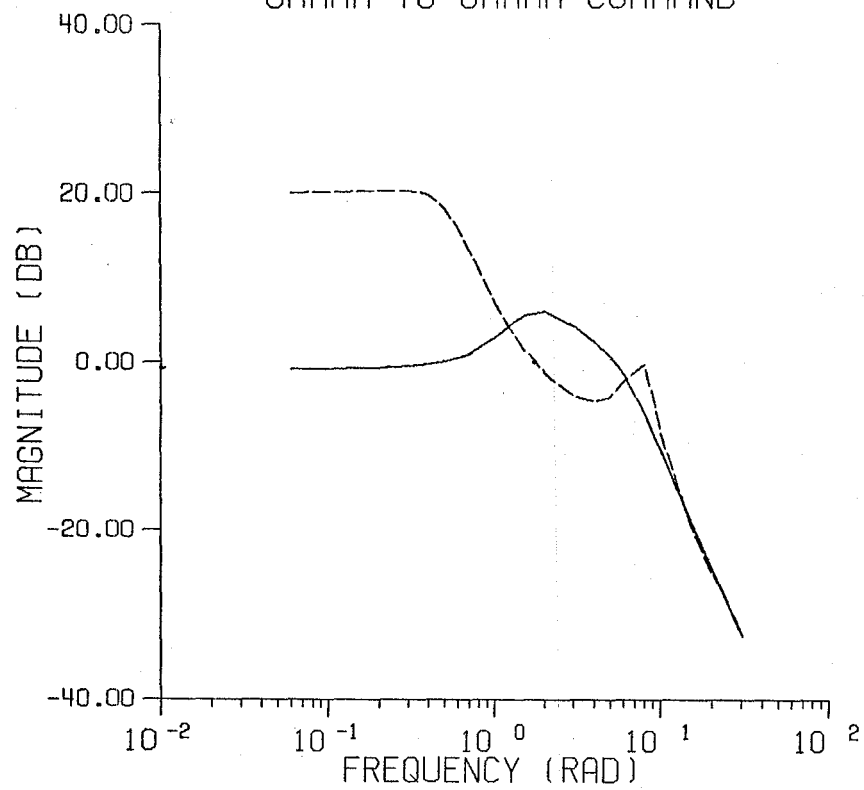
CONFIGURATION 4-1 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



CONFIGURATION 5-1 GAMMA TRACKING

GAMMA TO GAMMA COMMAND



ALTITUDE TRACKING

CONFIGURATION	SENSITIVITY (db)	SENSITIVITY (abs)
2-1	.418	.747
2-2	-.105	-.153
2-3	2.281	3.925
3-1	.039	.072
3-2	.355	.639
3-3	.526	.787
4-1	1.953	3.166
5-1	-.009	-.019

RESONANT PEAK

2-1	5.177
2-2	3.446
2-3	4.423
3-1	5.582
3-2	5.253
3-3	3.605
4-1	3.987
5-1	6.993

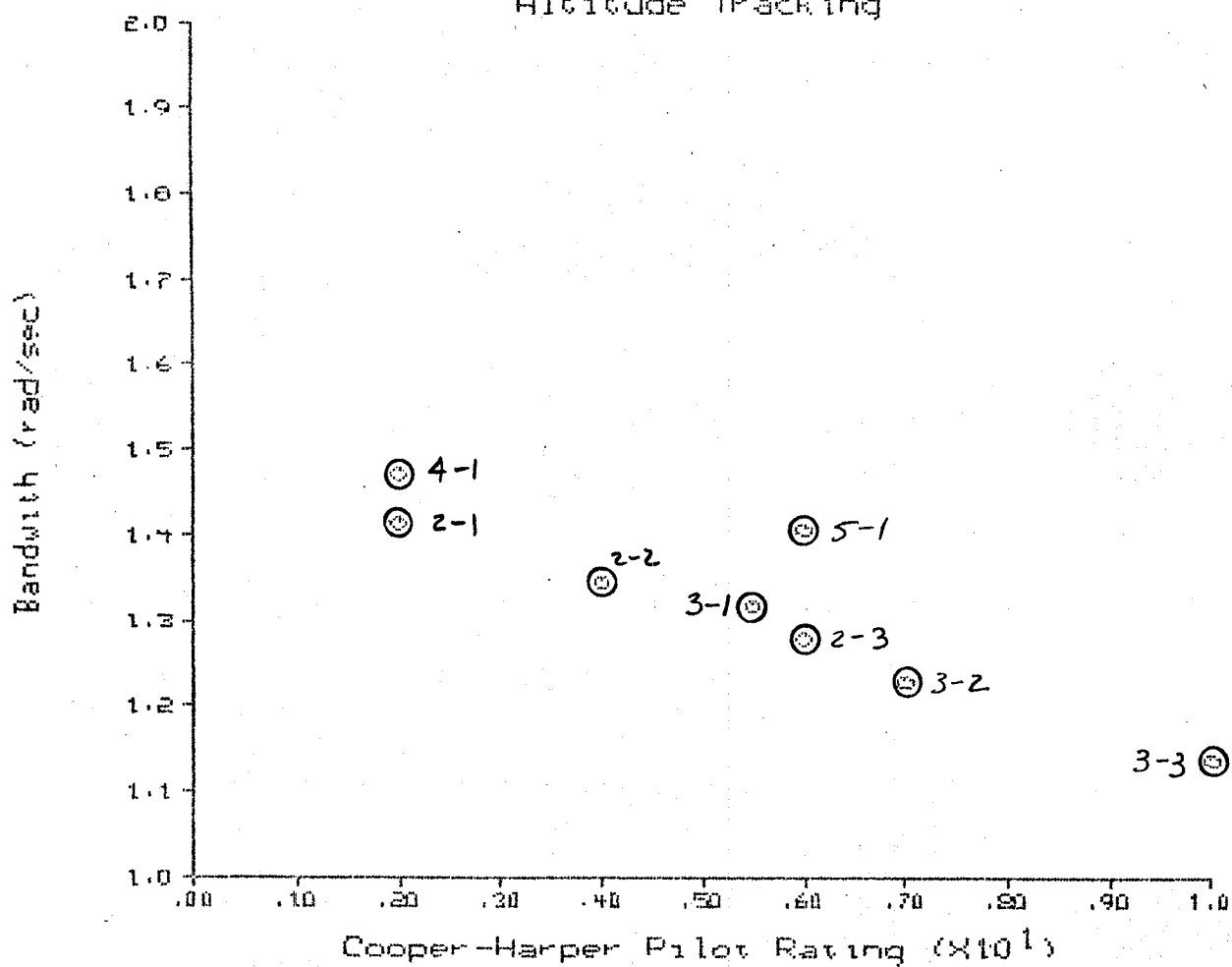
ALTITUDE TRACKING

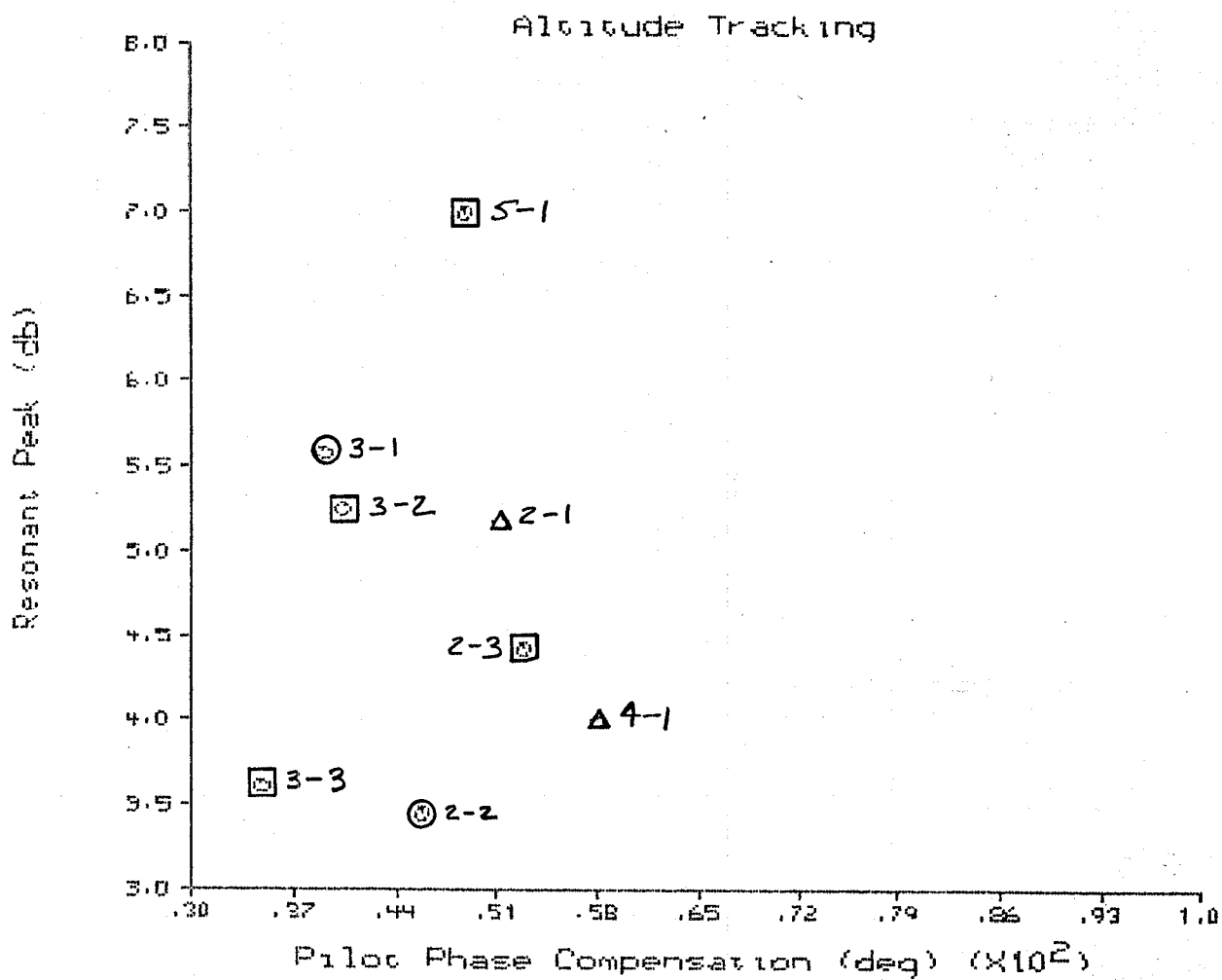
CONFIGURATION	PILOTS h_{ERROR} COMPENSATION	SINGLE PILOT T.F. (Phase)
2-1	51.256 (deg)	104.311 (deg)
2-2	45.752	90.673
2-3	52.879	93.491
3-1	39.026	53.449
3-2	40.316	57.611
3-3	34.689	68.201
4-1	57.968	112.228
5-1	48.737	53.474

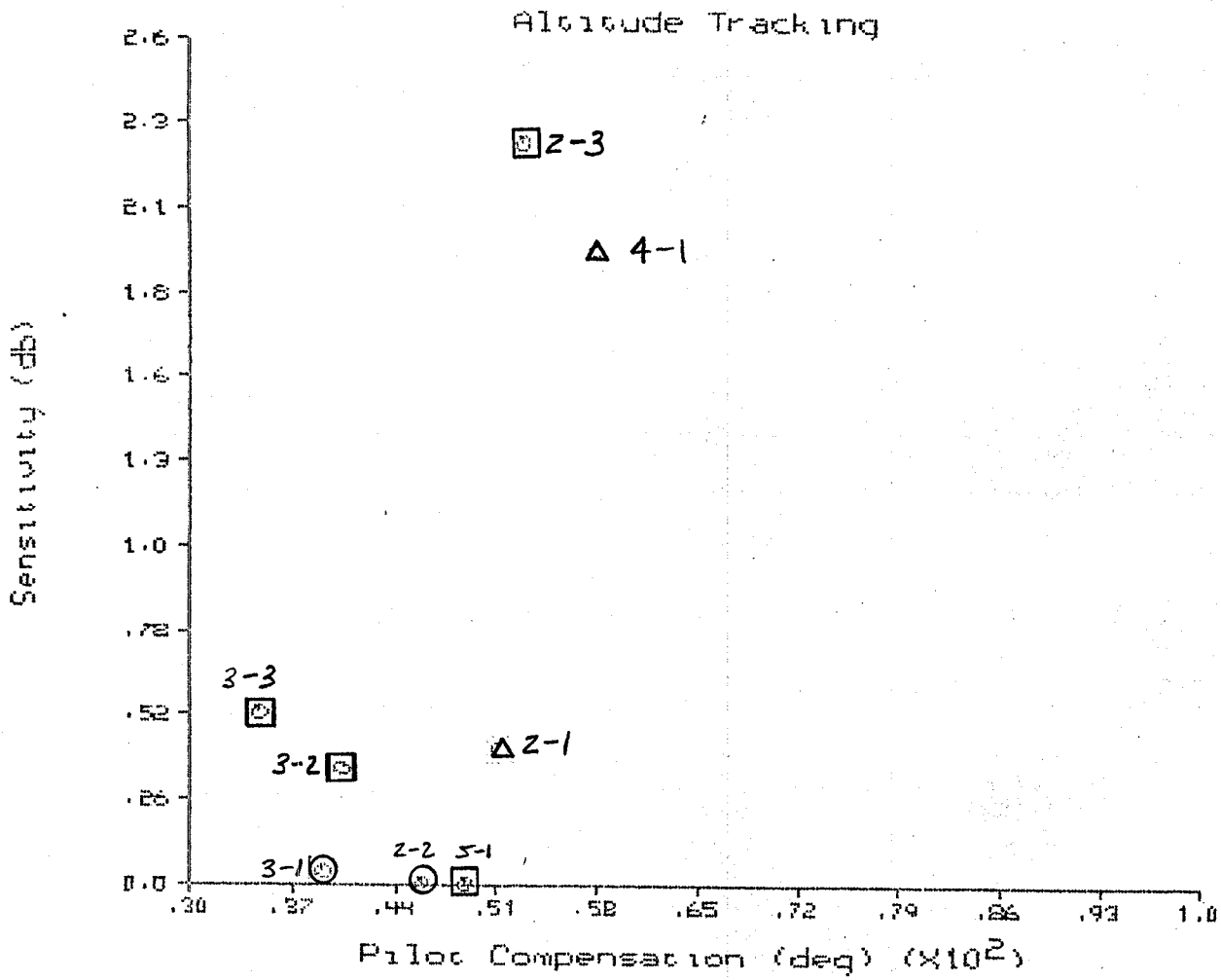
CONFIGURATION	BANDWIDTH (RAD/SEC)	
2-1	1.413	2
2-2	1.344	4
2-3	1.279	6
3-1	1.317	5.5
3-2	1.228	7
3-3	1.136	10
4-1	1.472	2
5-1	1.406	6

Note: Config. 1-1 did not come close enough to converge an altitude tracking to include.

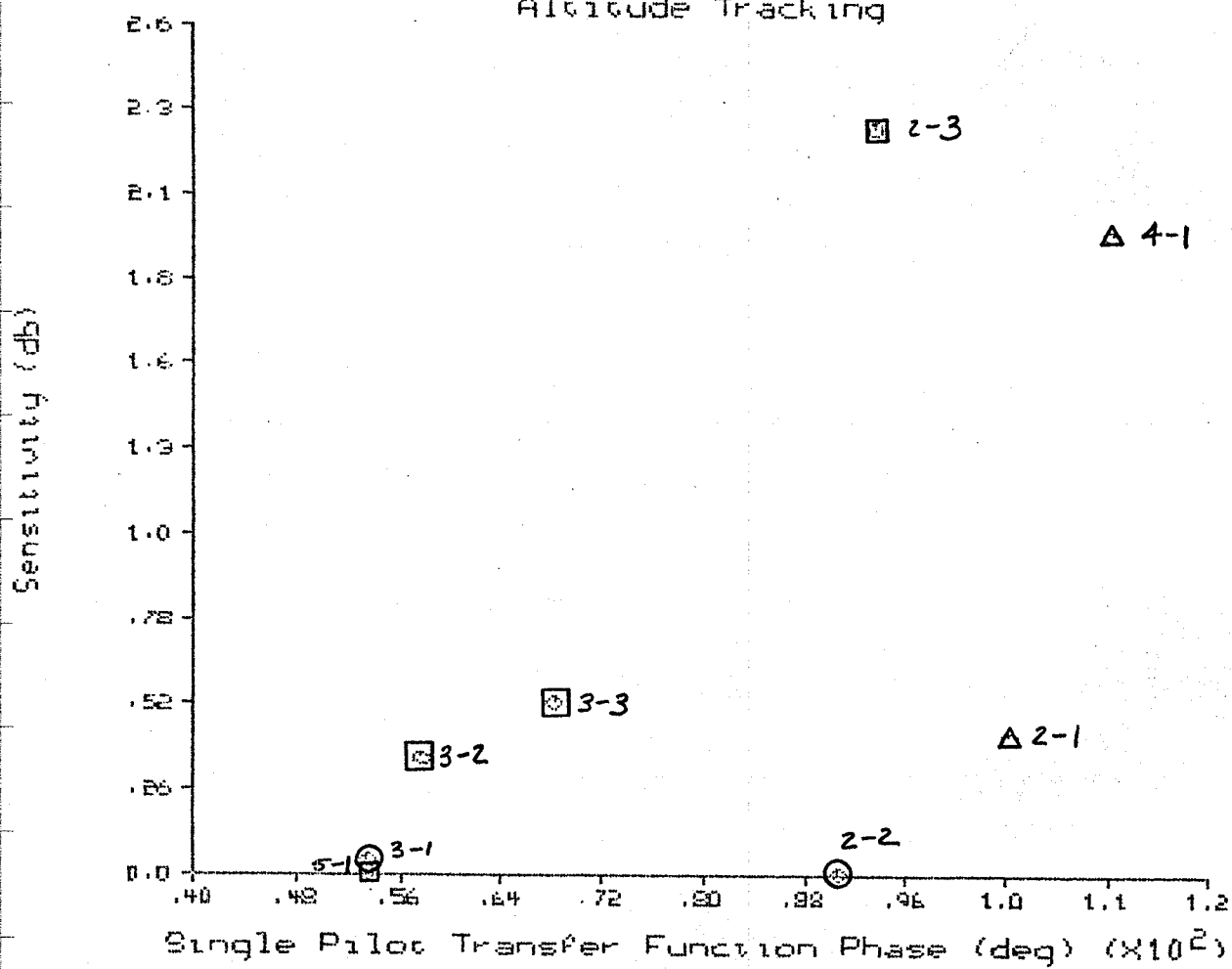
Altitude Tracking



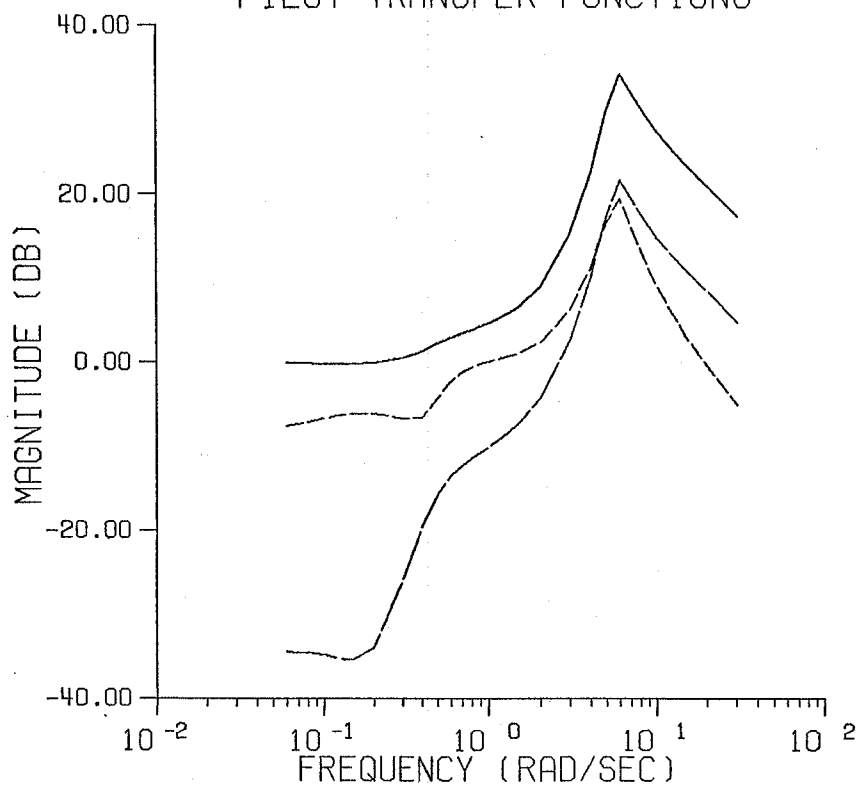




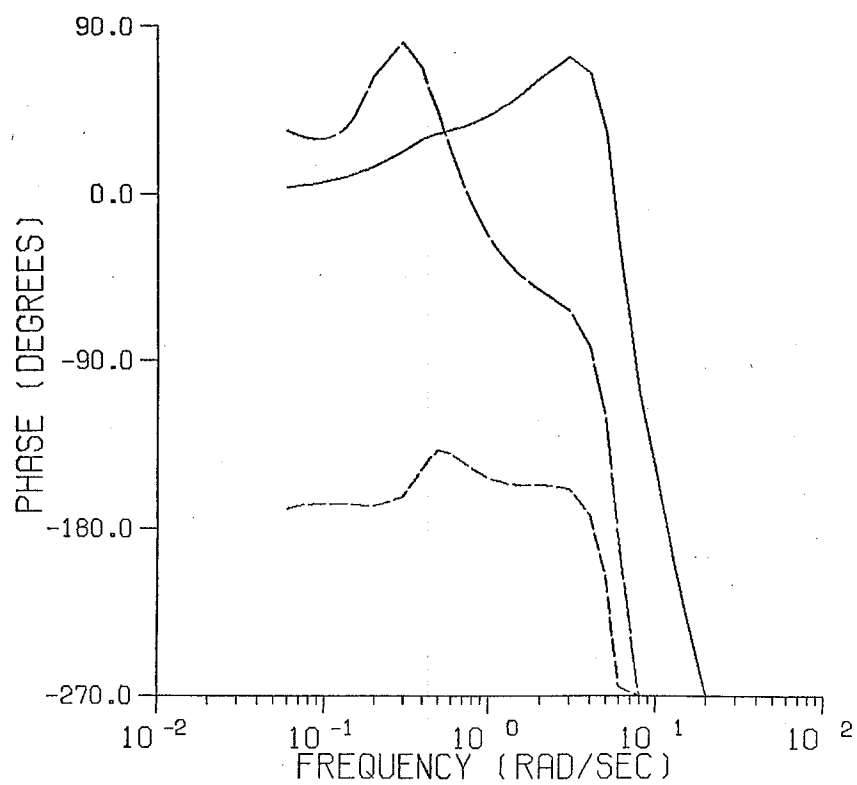
Altitude Tracking



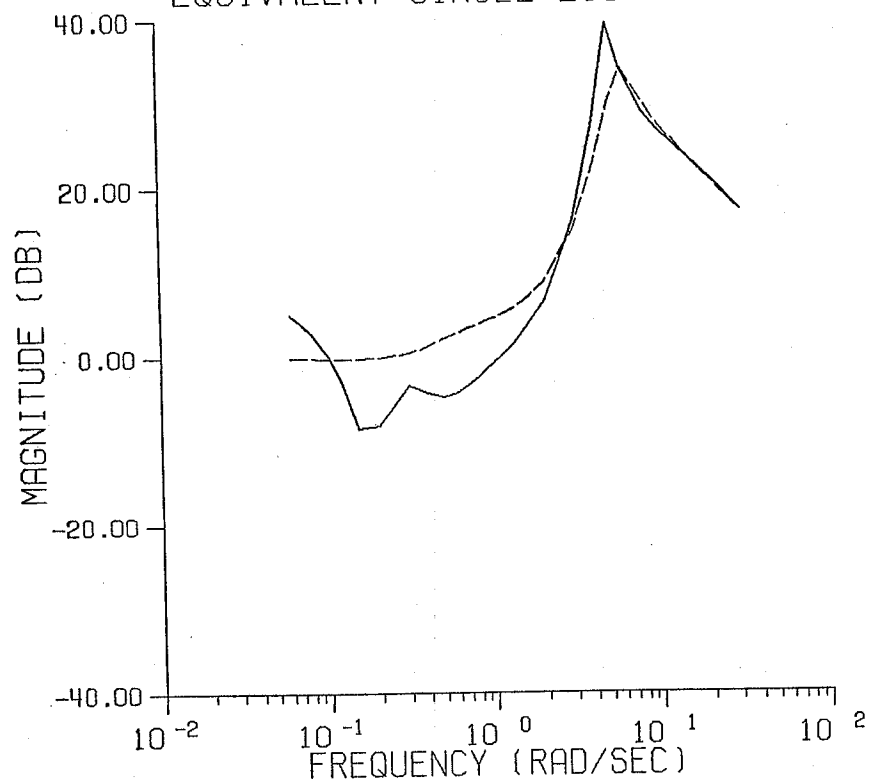
CONFIGURATION 2-1 ALTITUDE TRACKING
PILOT TRANSFER FUNCTIONS



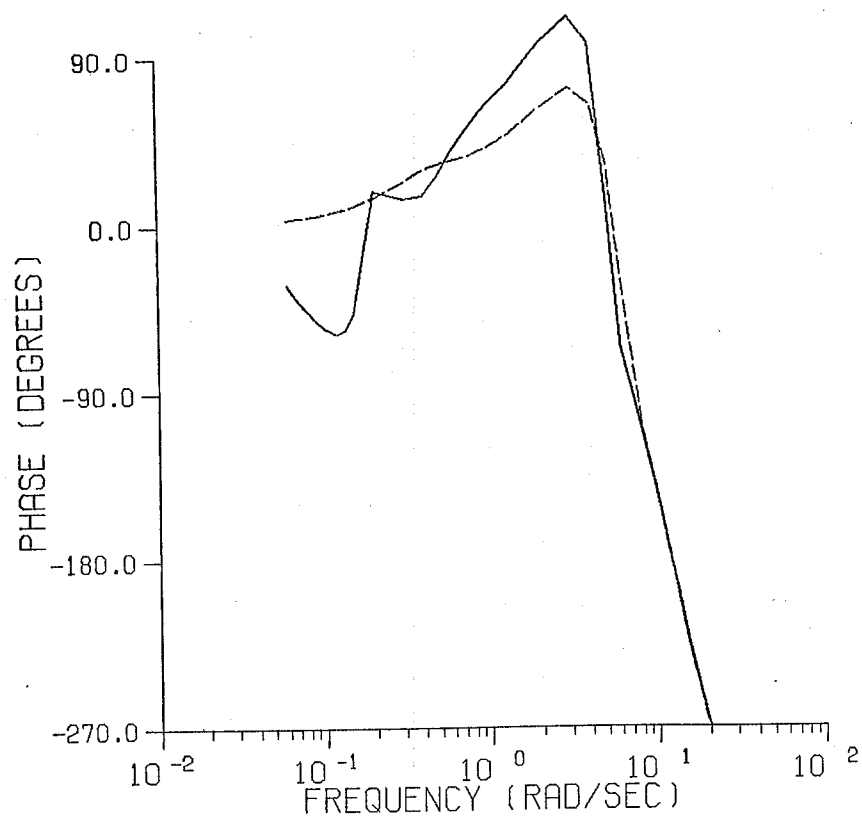
——— ERROR RESPONSE
----- THETA RESPONSE
-.-.-.- ALTITUDE RESPONSE



CONFIGURATION 2-1 ALTITUDE TRACKING
EQUIVALENT SINGLE LOOP PILOT FUNCTION

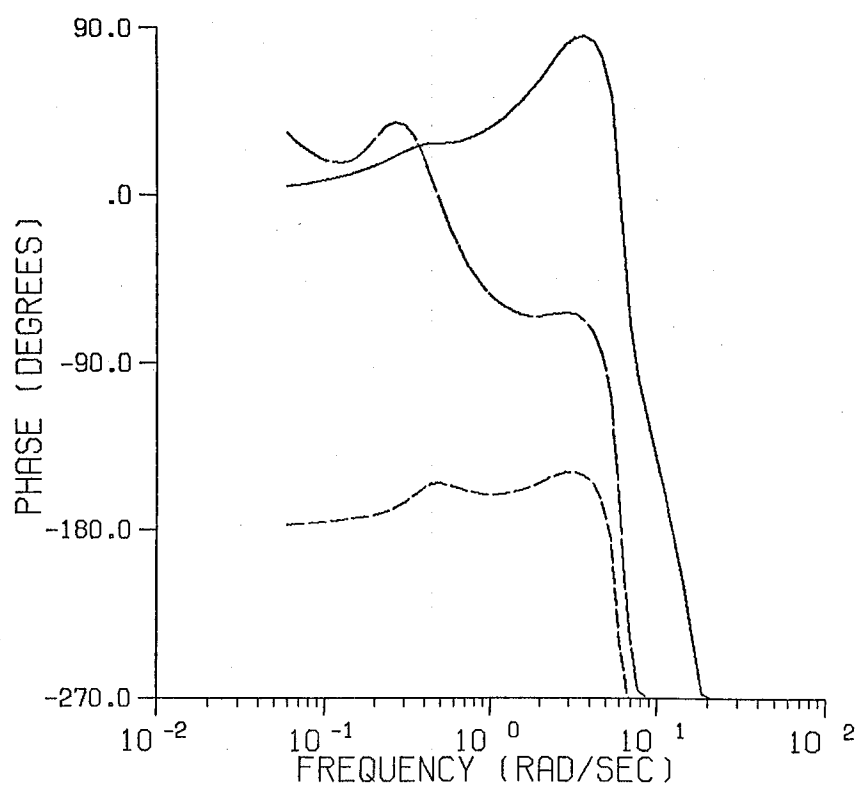
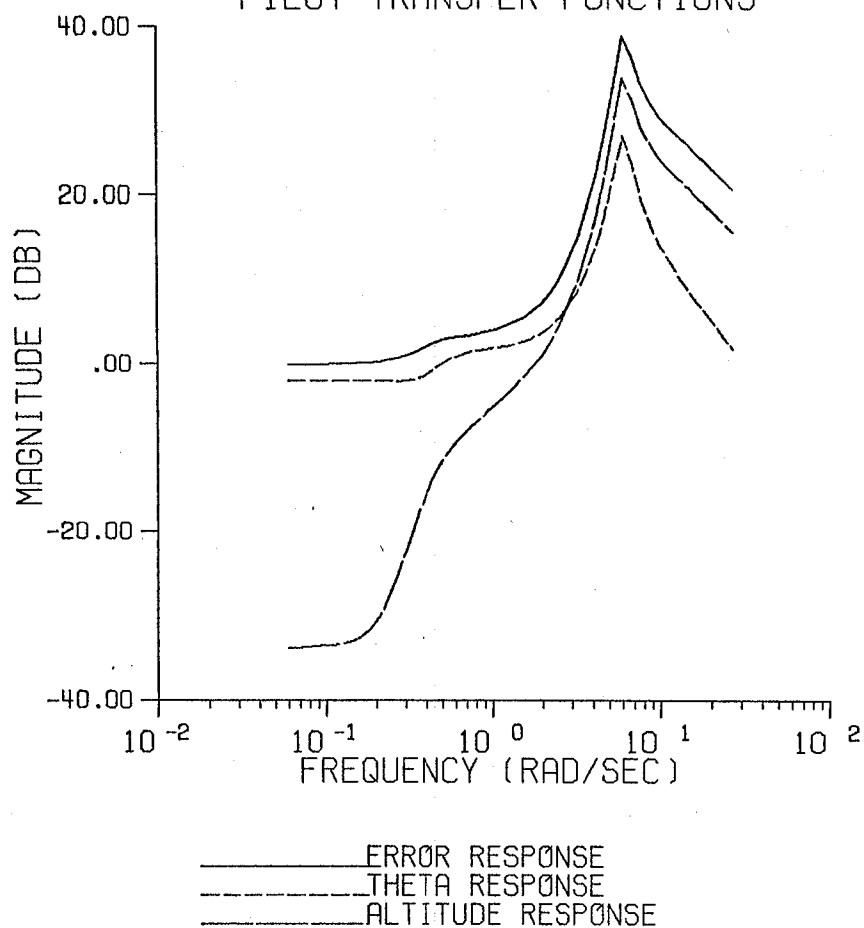


—— SINGLE PILOT FUNCTION
----- ERROR COMPENSATION

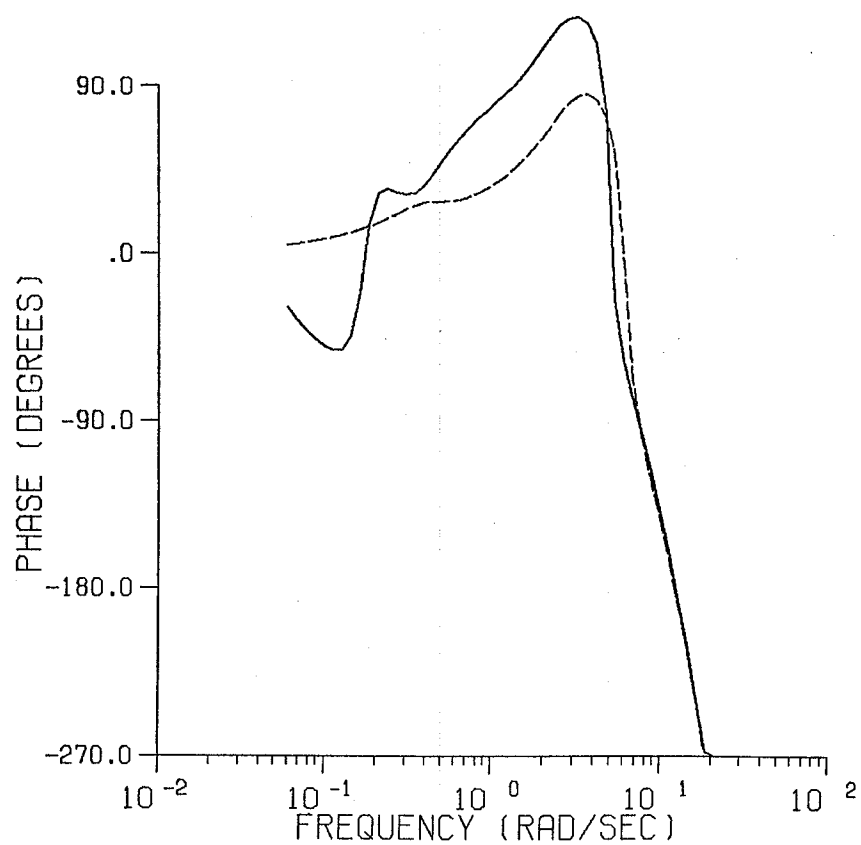
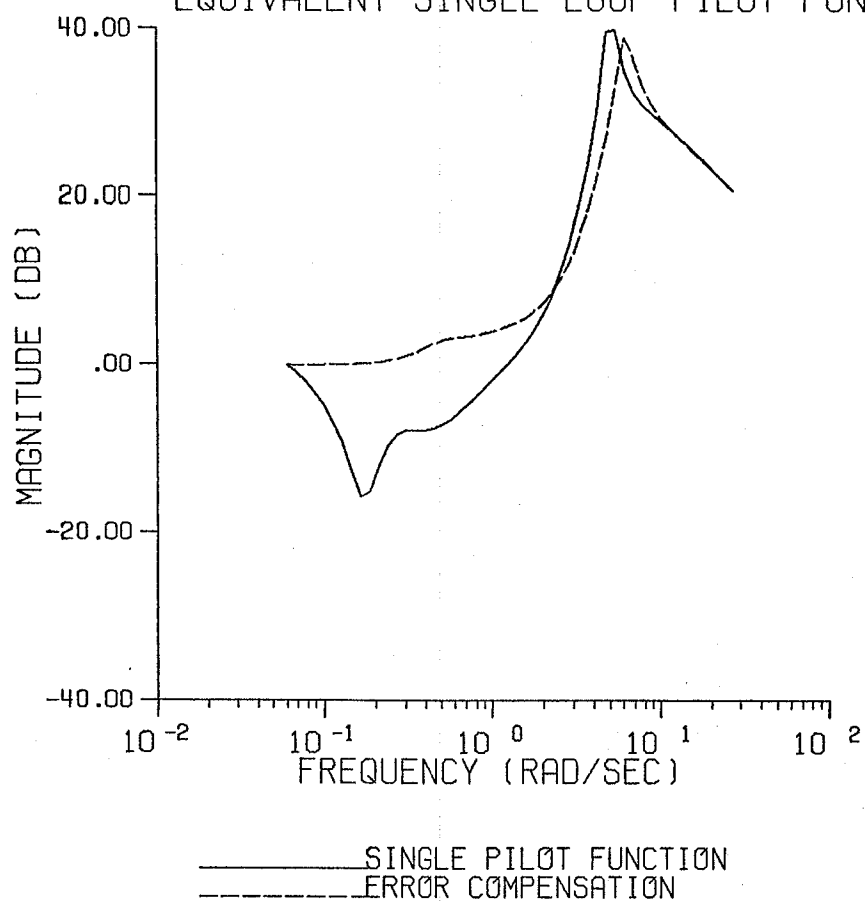


CONFIGURATION 2-2 ALTITUDE TRACKING

PILOT TRANSFER FUNCTIONS

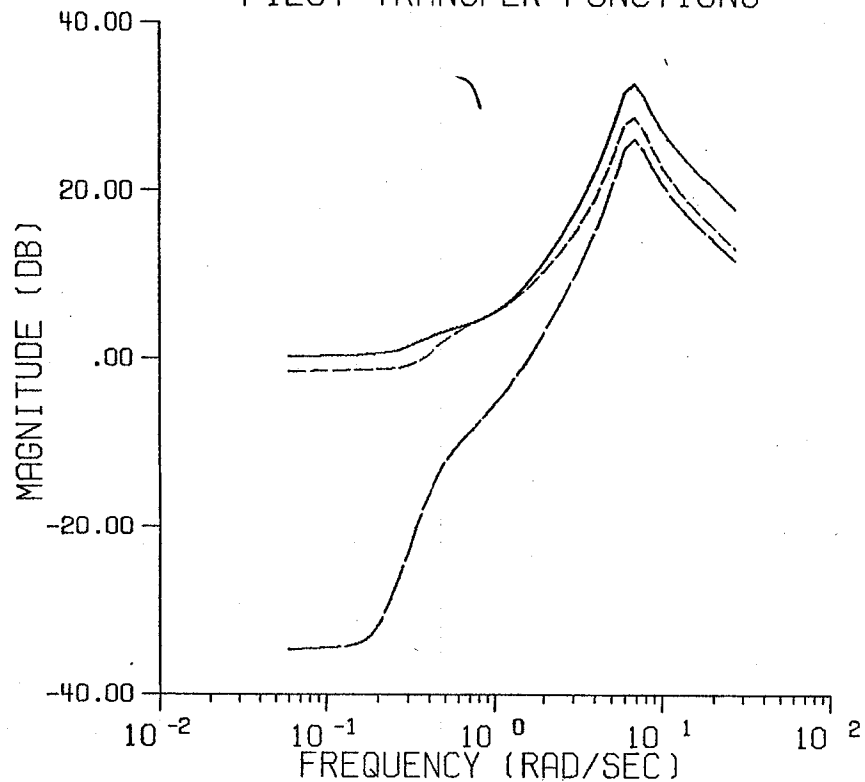


CONFIGURATION 2-2 ALTITUDE TRACKING
EQUIVALENT SINGLE LOOP PILOT FUNCTION

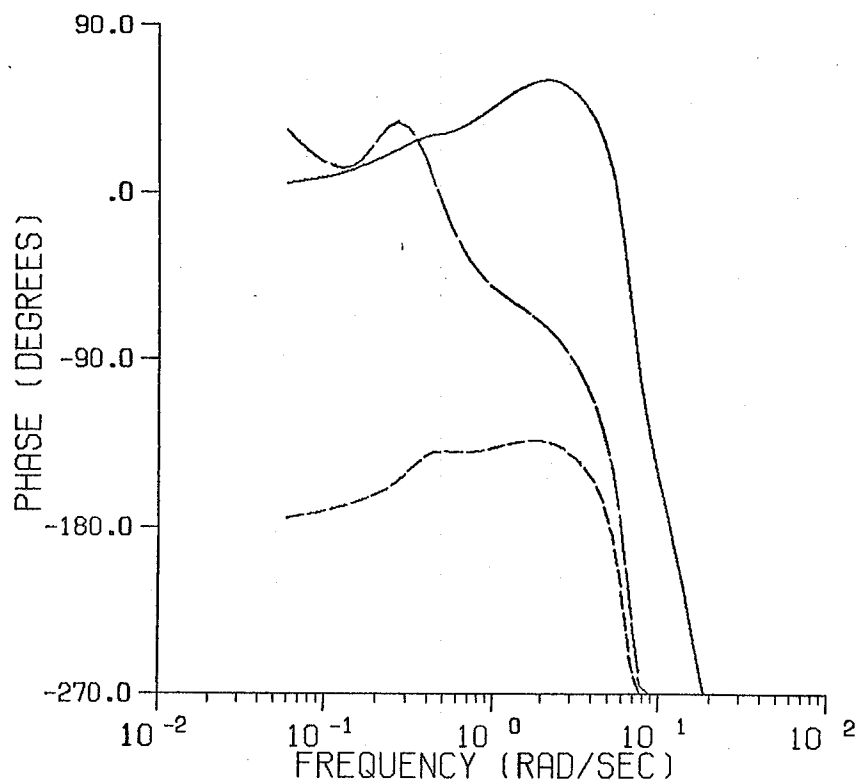


CONFIGURATION 2-3 ALTITUDE TRACKING

PILOT TRANSFER FUNCTIONS

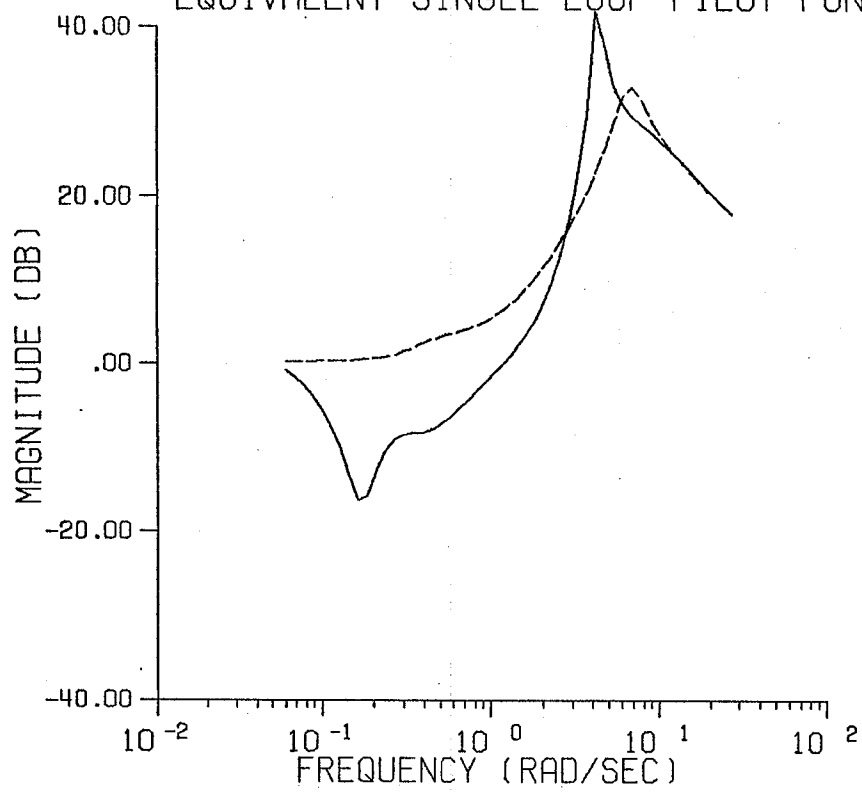


——— ERROR RESPONSE
----- THETA RESPONSE
- . - . - ALTITUDE RESPONSE

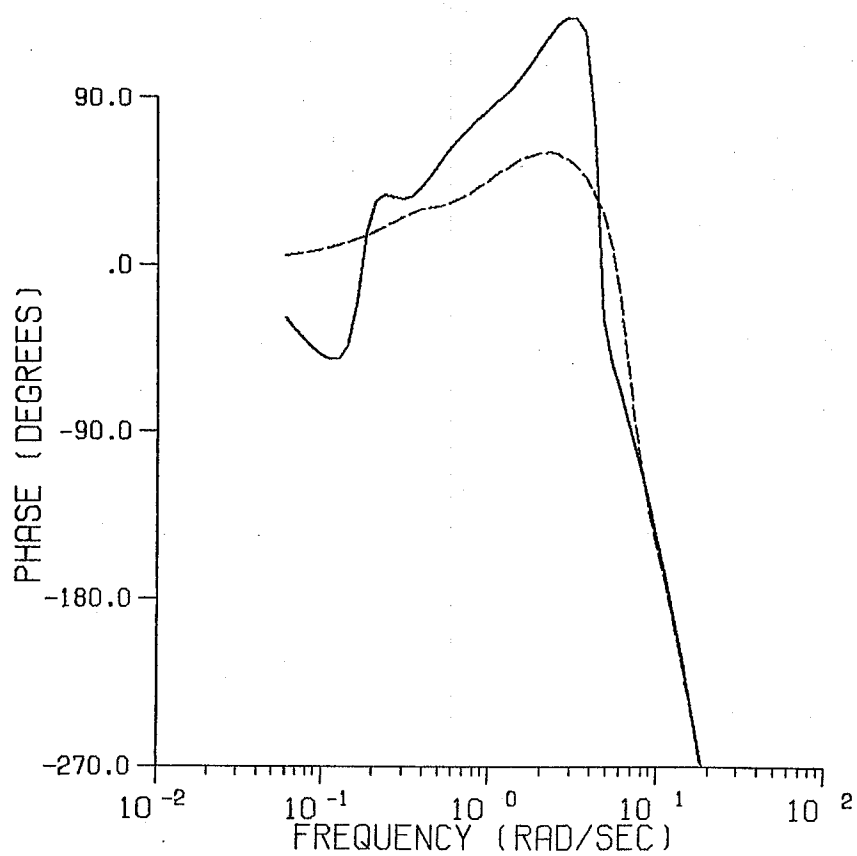


CONFIGURATION 2-3 ALTITUDE TRACKING

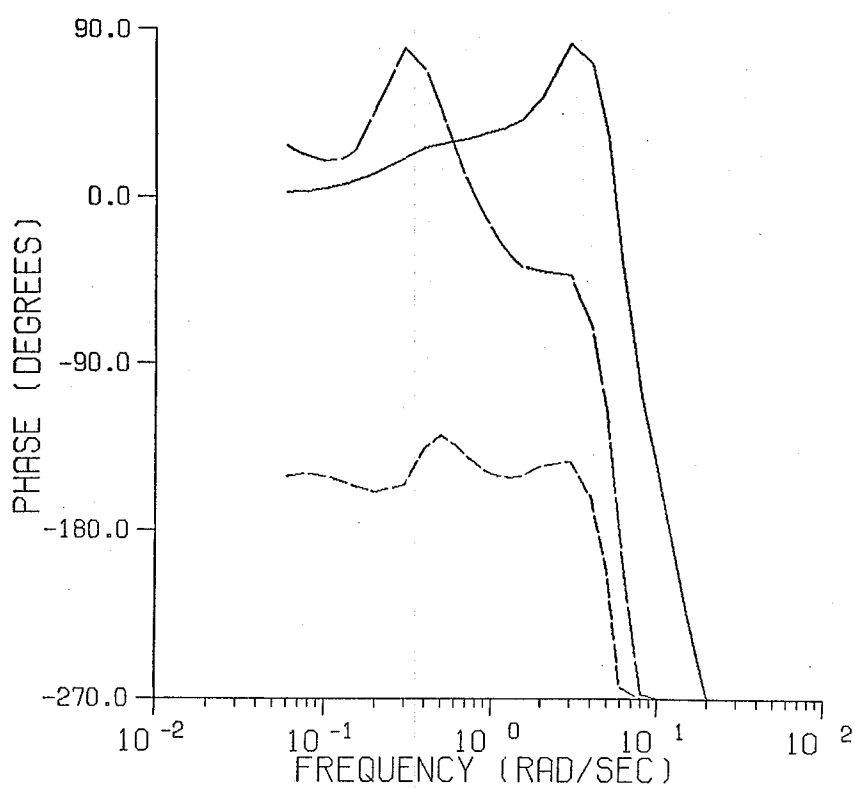
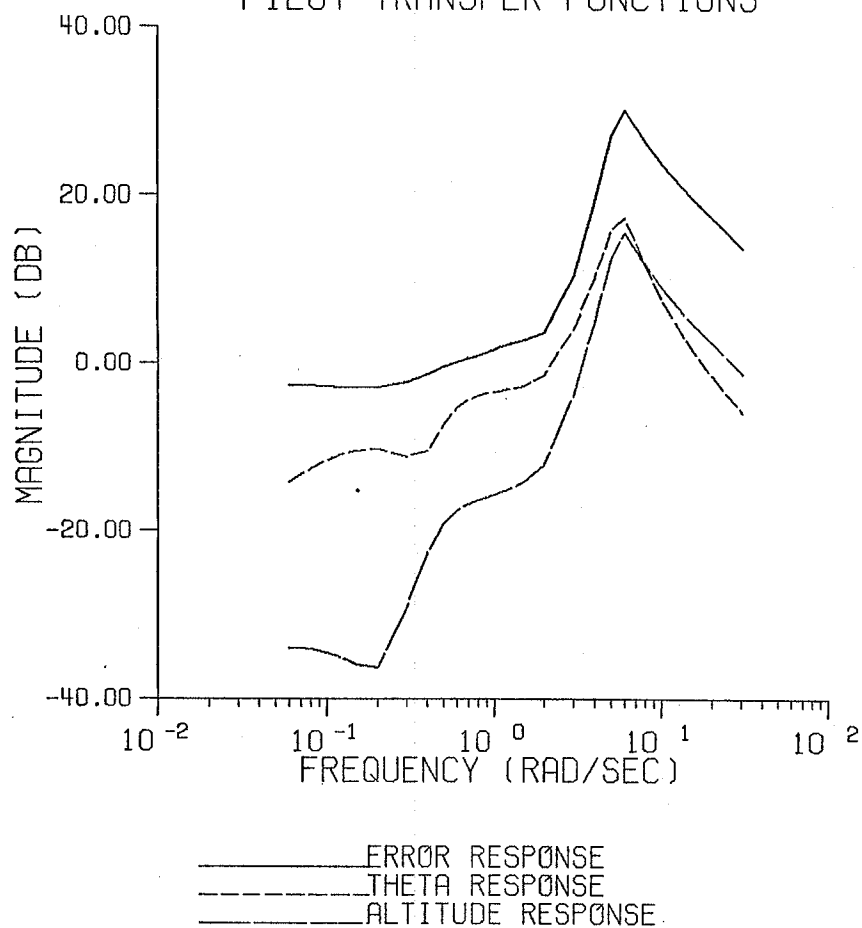
EQUIVALENT SINGLE LOOP PILOT FUNCTION



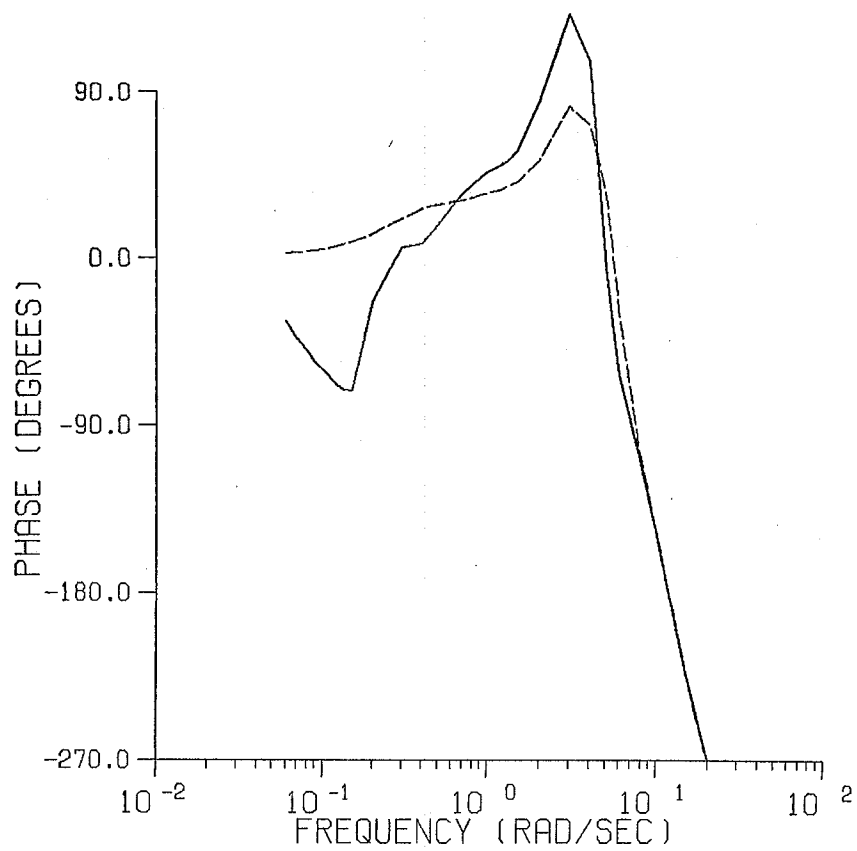
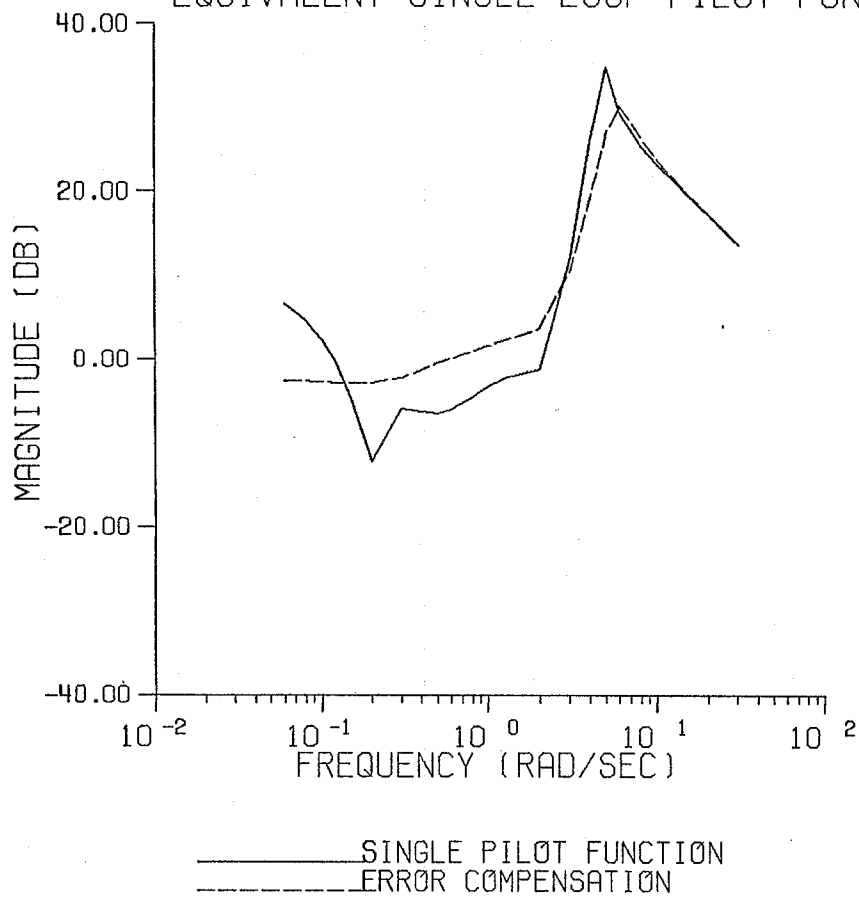
— SINGLE PILOT FUNCTION
- - - ERROR COMPENSATION



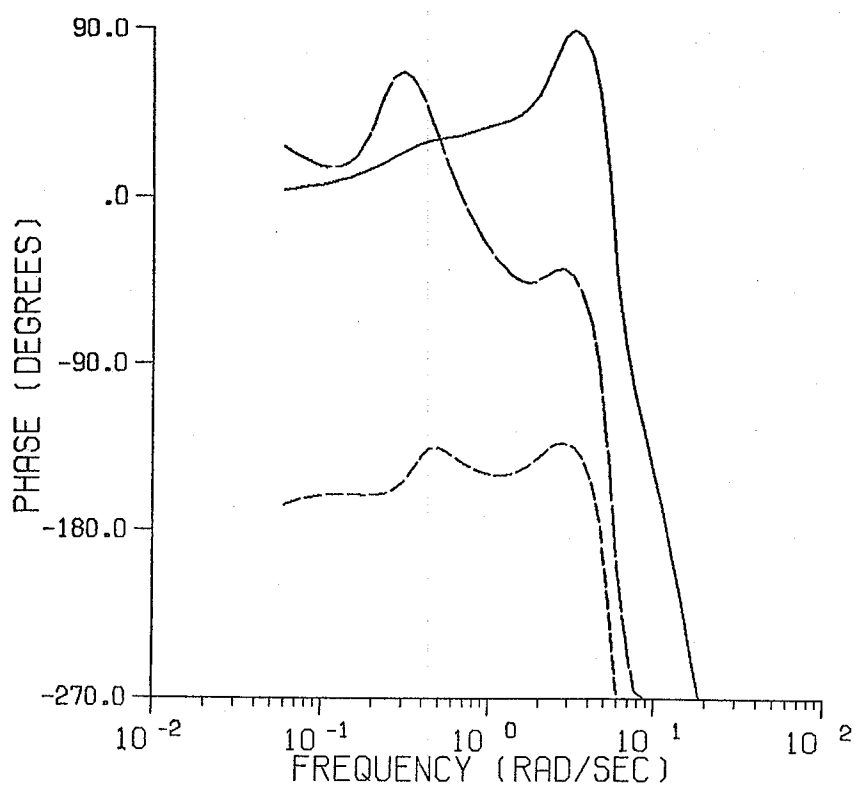
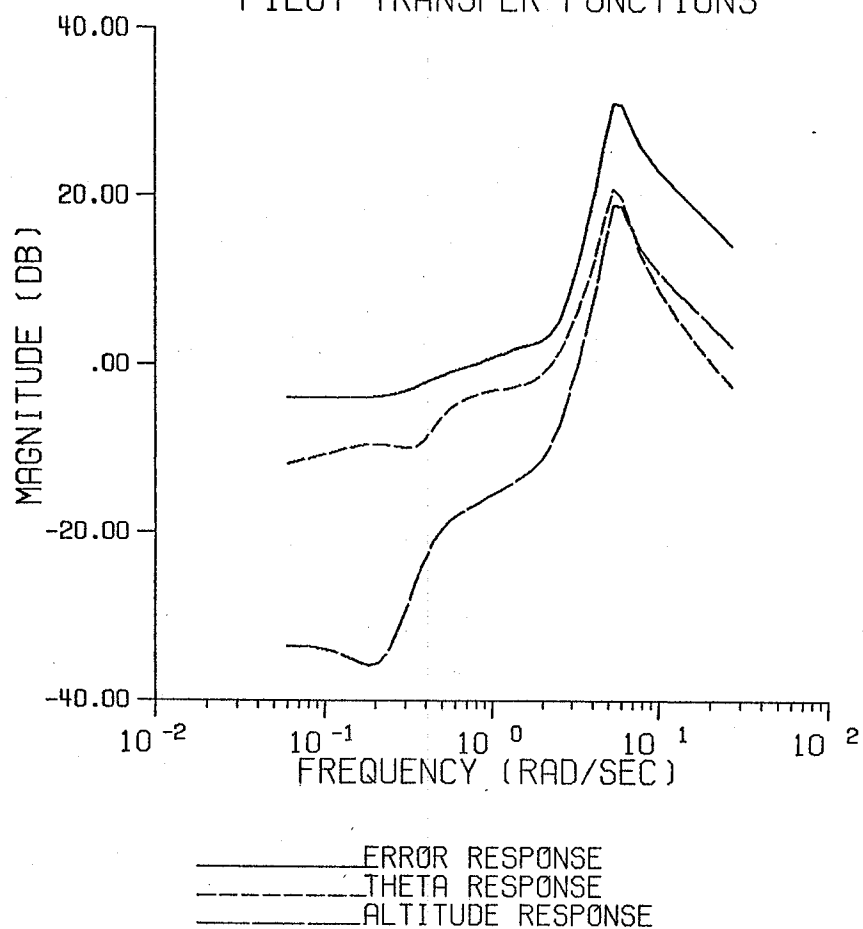
CONFIGURATION 3-1 ALTITUDE TRACKING
PILOT TRANSFER FUNCTIONS



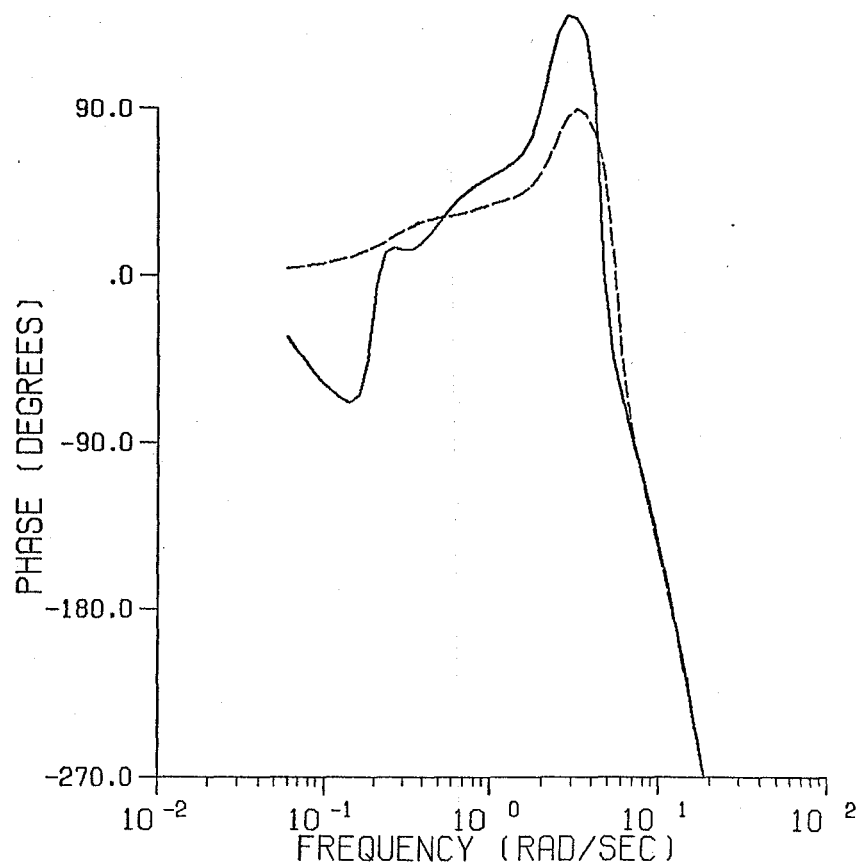
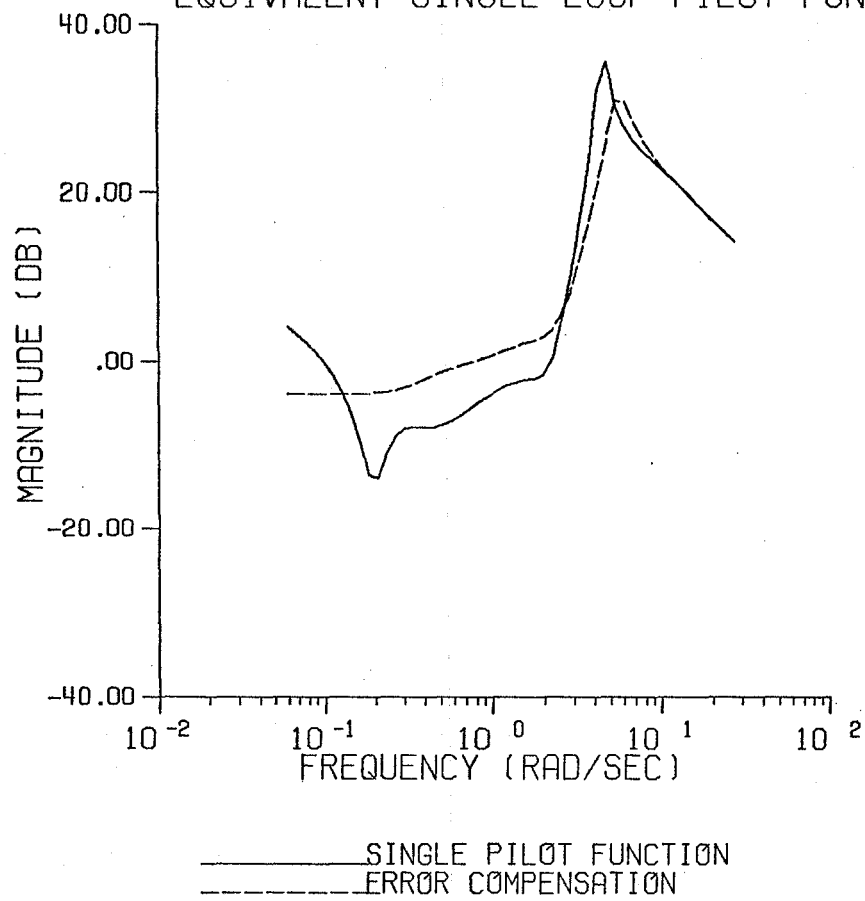
CONFIGURATION 3-1 ALTITUDE TRACKING
EQUIVALENT SINGLE LOOP PILOT FUNCTION



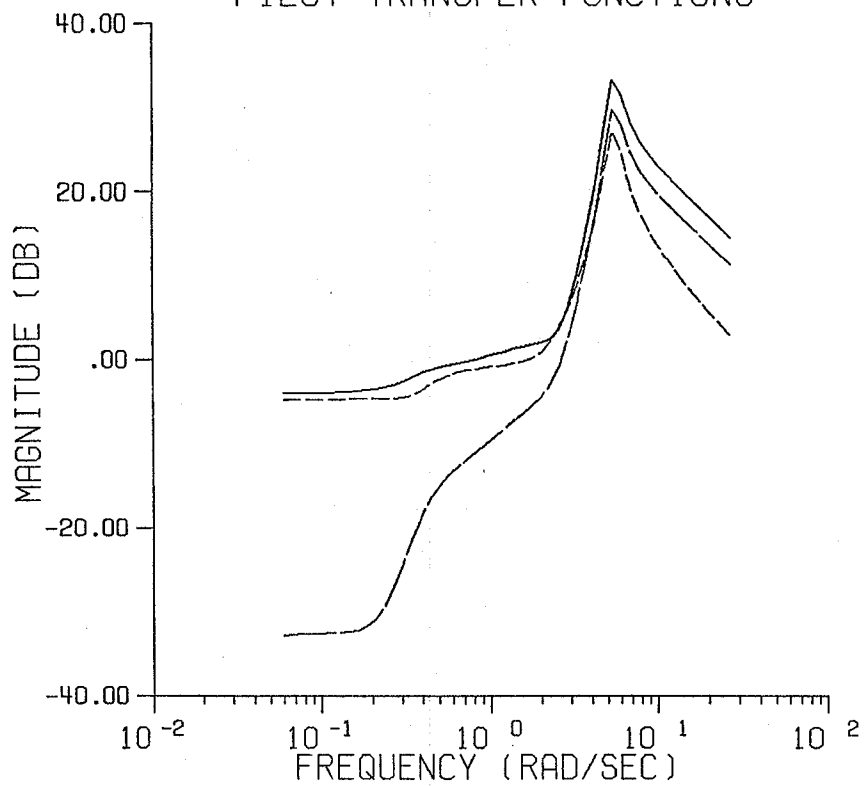
CONFIGURATION 3-2 ALTITUDE TRACKING
PILOT TRANSFER FUNCTIONS



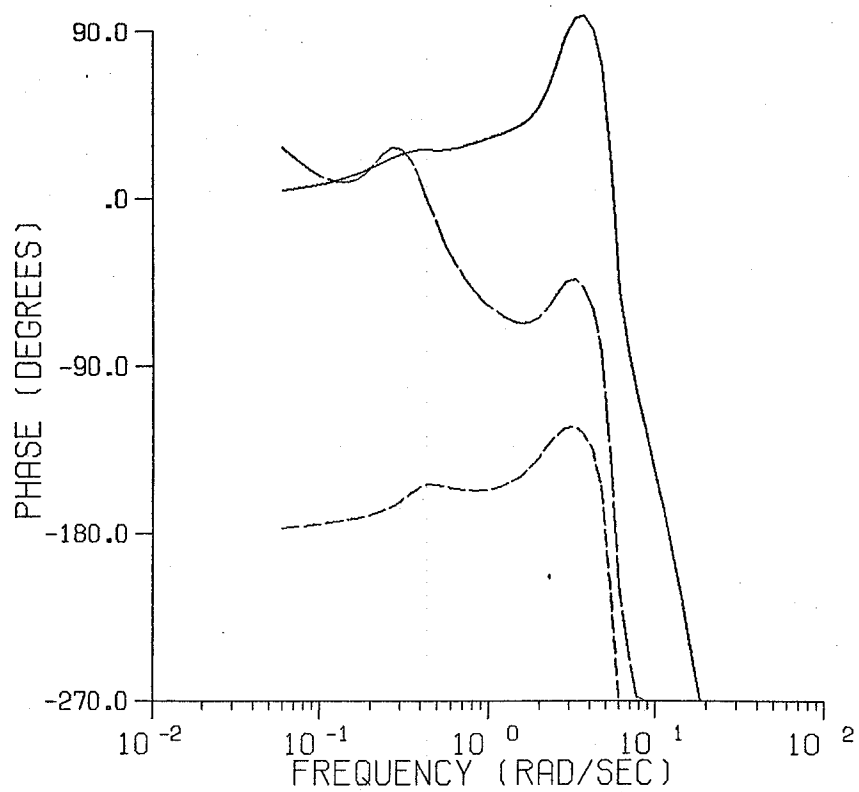
CONFIGURATION 3-2 ALTITUDE TRACKING
EQUIVALENT SINGLE LOOP PILOT FUNCTION



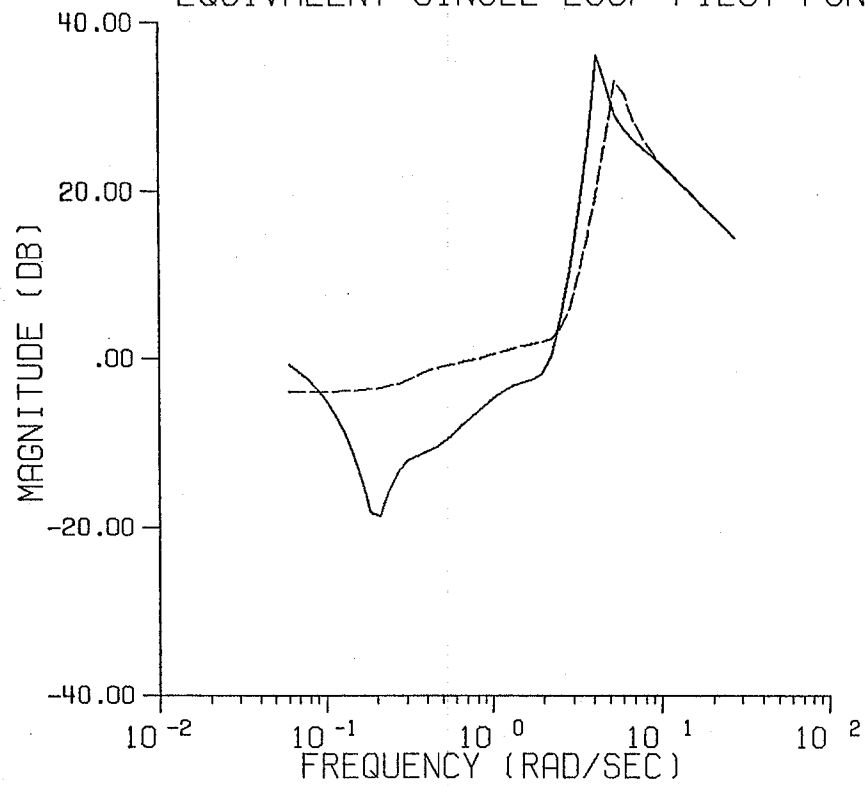
CONFIGURATION 3-3 ALTITUDE TRACKING
PILOT TRANSFER FUNCTIONS



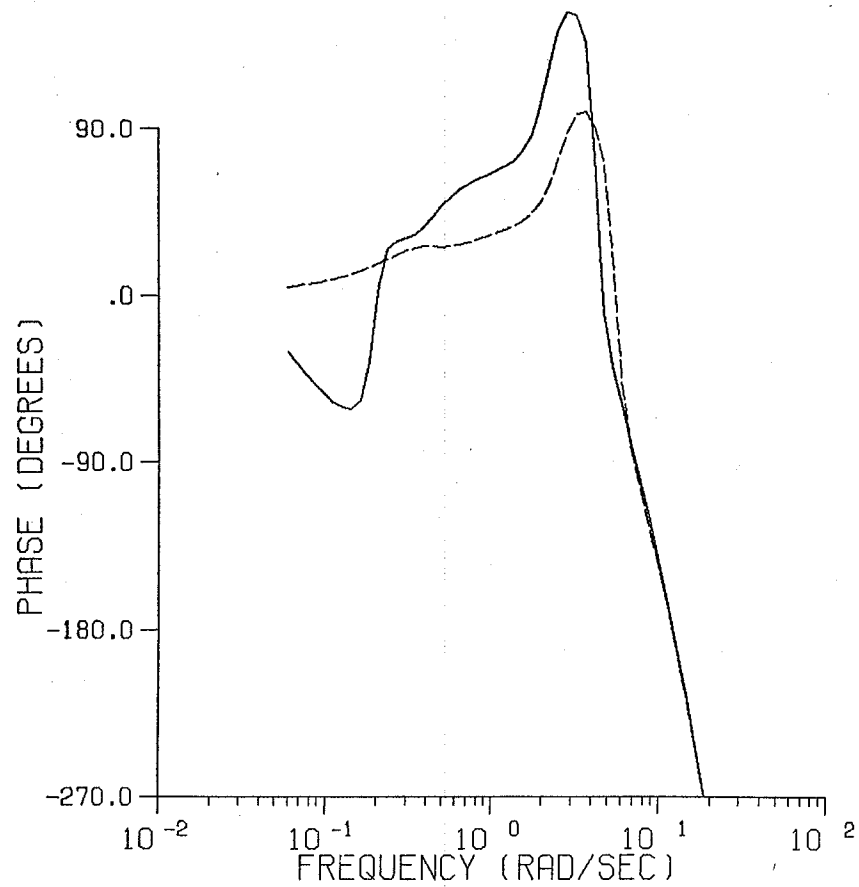
——— ERROR RESPONSE
----- THETA RESPONSE
-.-.- ALTITUDE RESPONSE



CONFIGURATION 3-3 ALTITUDE TRACKING
EQUIVALENT SINGLE LOOP PILOT FUNCTION

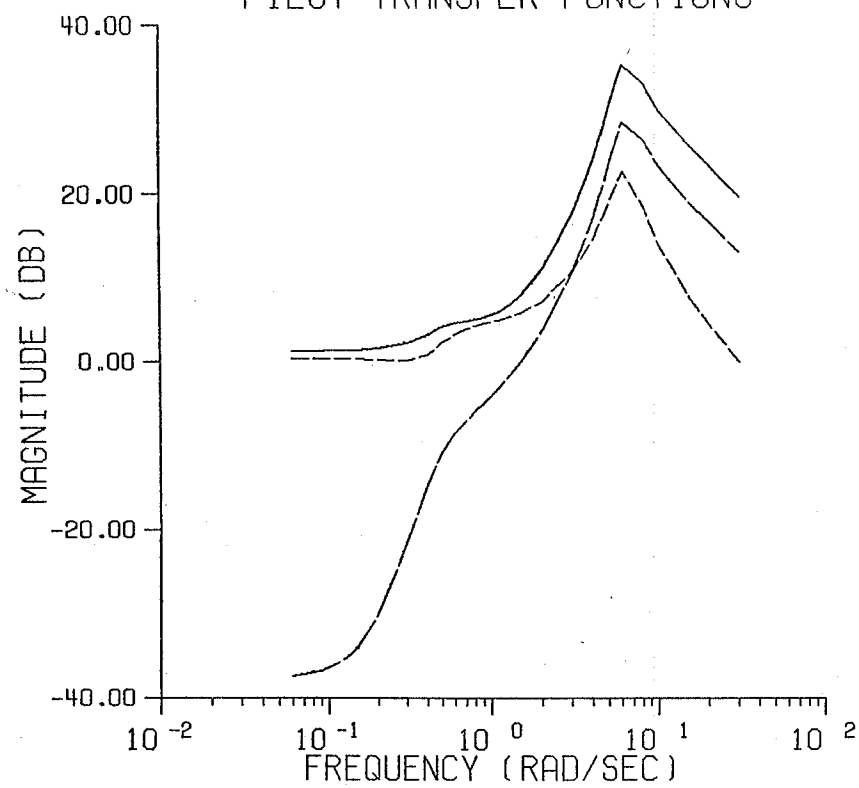


— SINGLE PILOT FUNCTION
- - - ERROR COMPENSATION

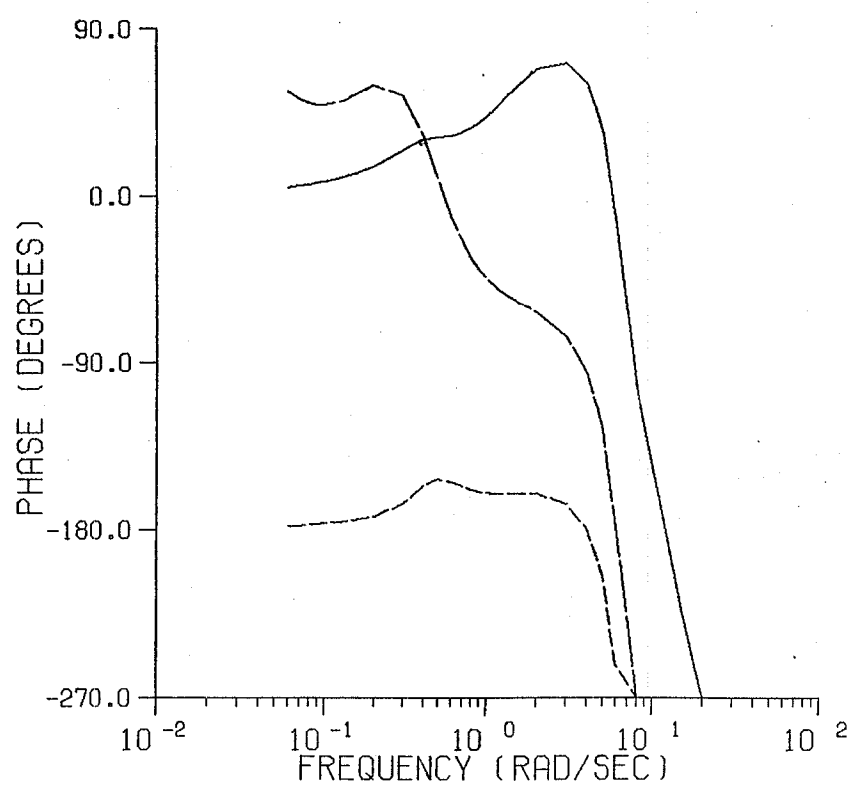


CONFIGURATION 4-1 ALTITUDE TRACKING

PILOT TRANSFER FUNCTIONS

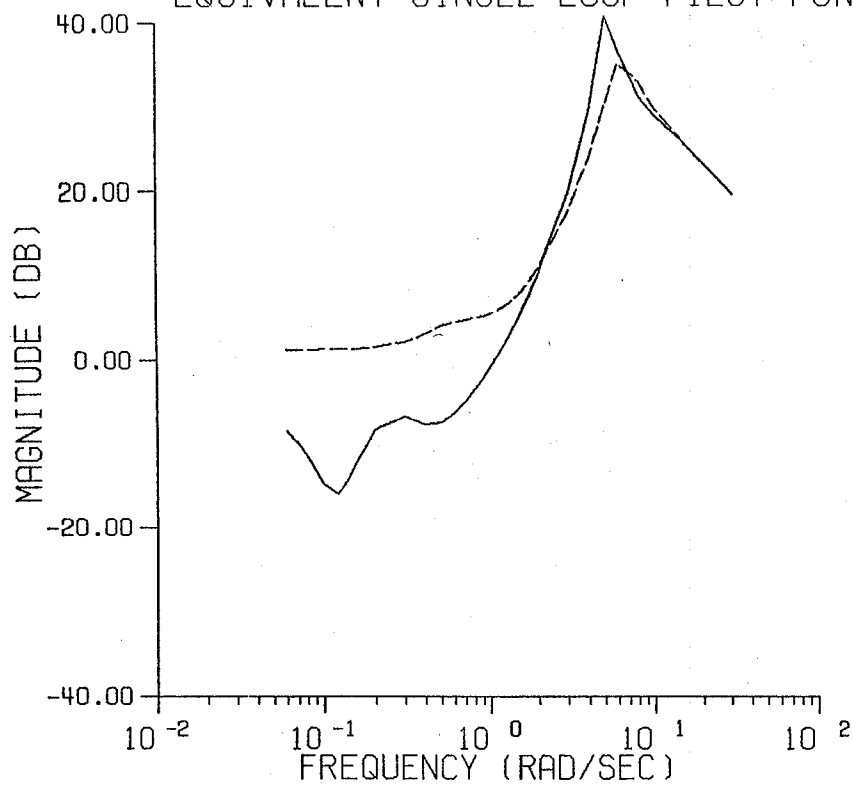


——— ERROR RESPONSE
----- THETA RESPONSE
----- ALTITUDE RESPONSE

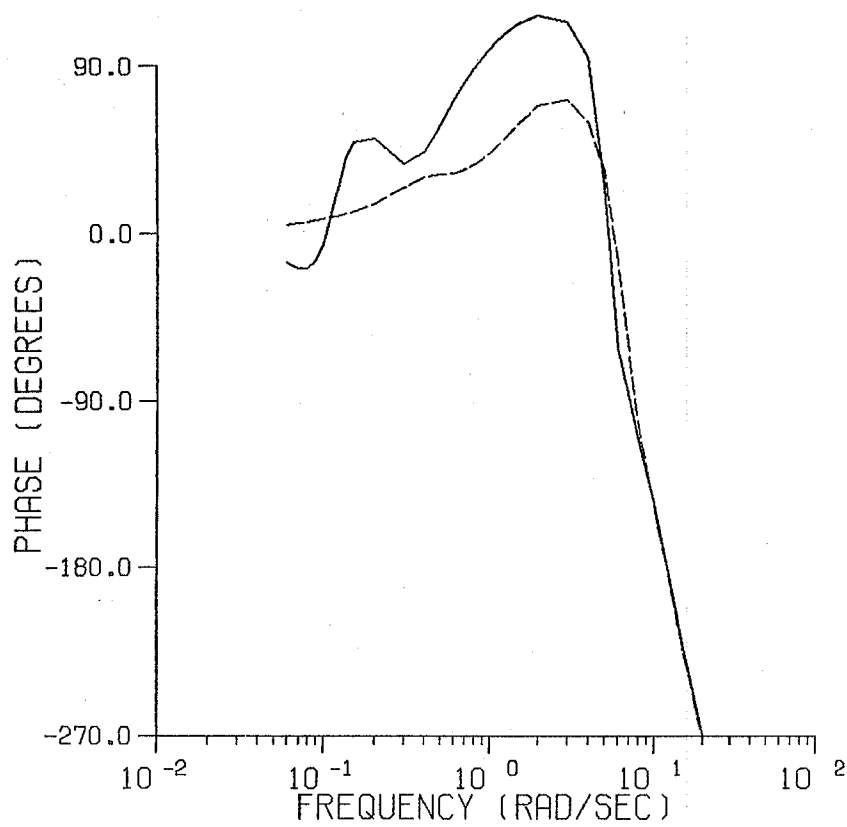


CONFIGURATION 4-1 ALTITUDE TRACKING

EQUIVALENT SINGLE LOOP PILOT FUNCTION

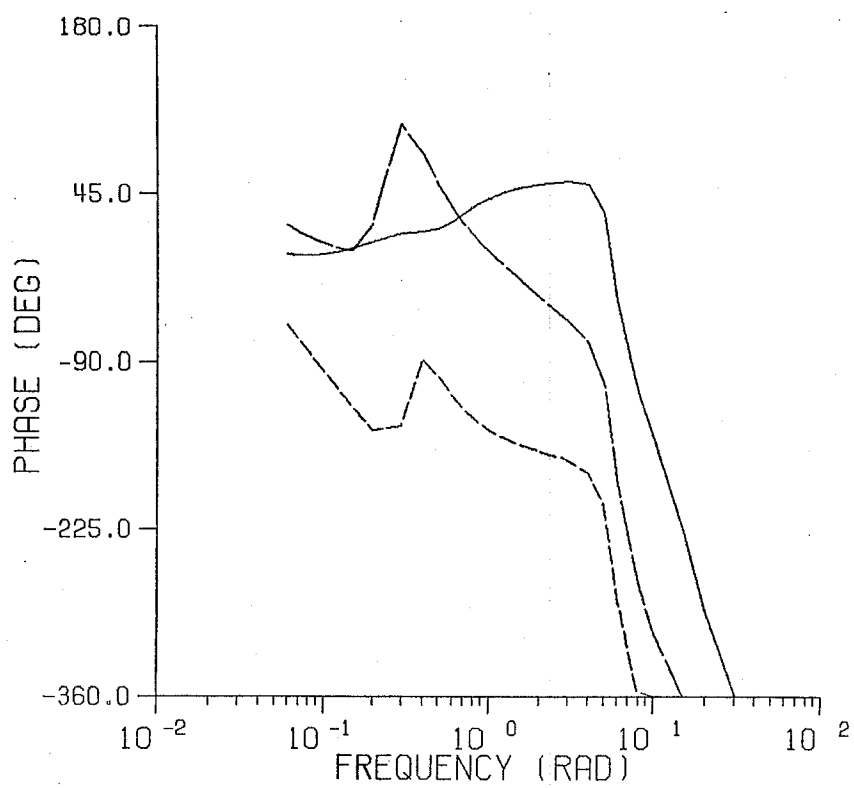
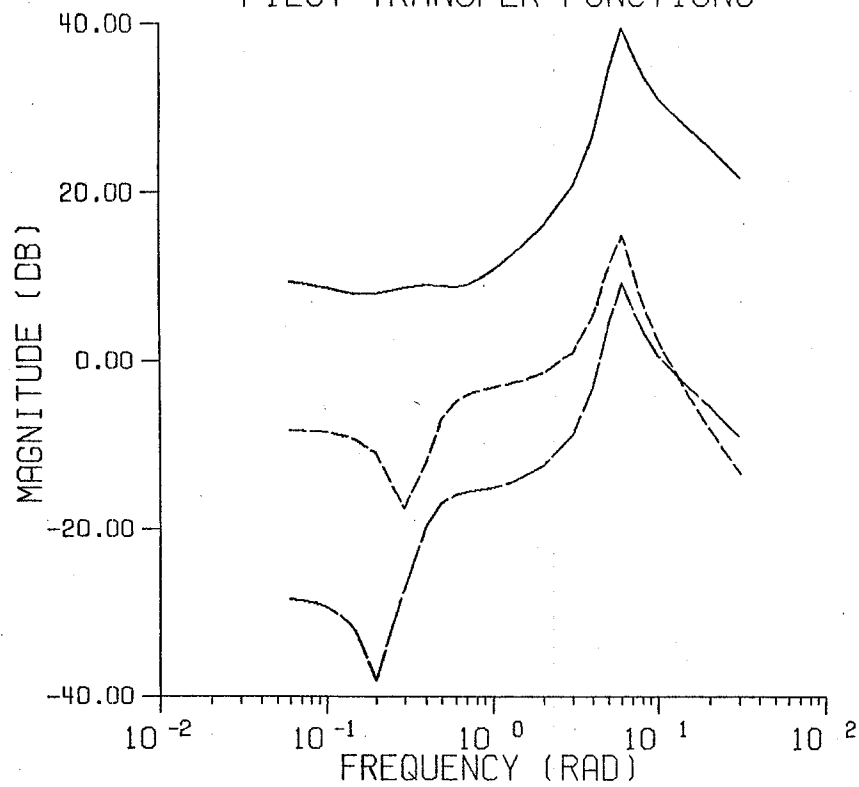


— SINGLE PILOT FUNCTION
- - - ERROR COMPENSATION

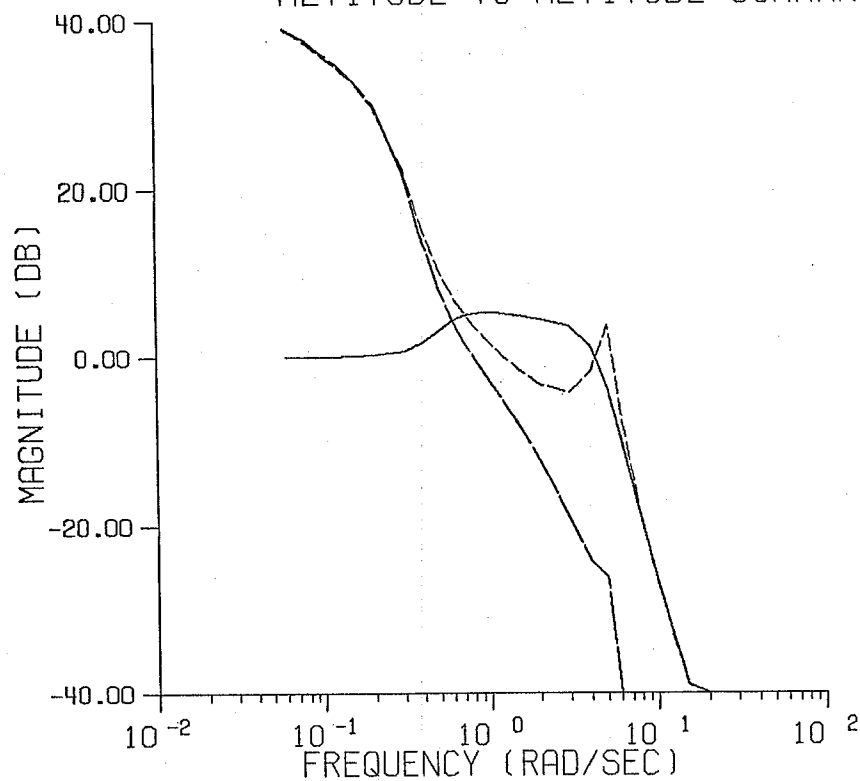


CONFIGURATION 5-1 ALTITUDE TRACKING

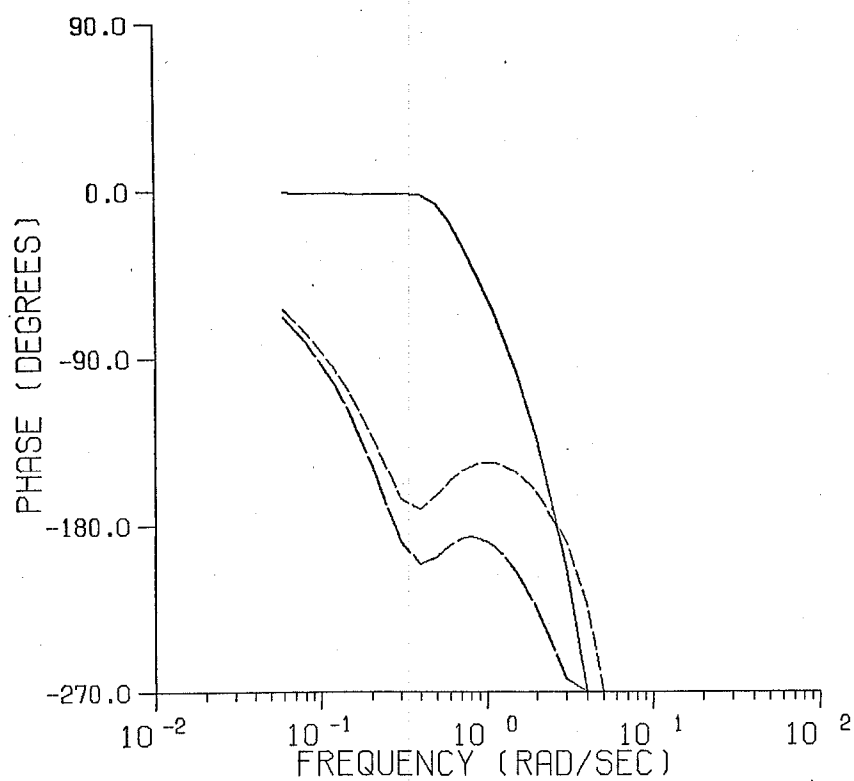
PILOT TRANSFER FUNCTIONS



CONFIGURATION 2-1 ALTITUDE TRACKING
ALTITUDE TO ALTITUDE COMMAND

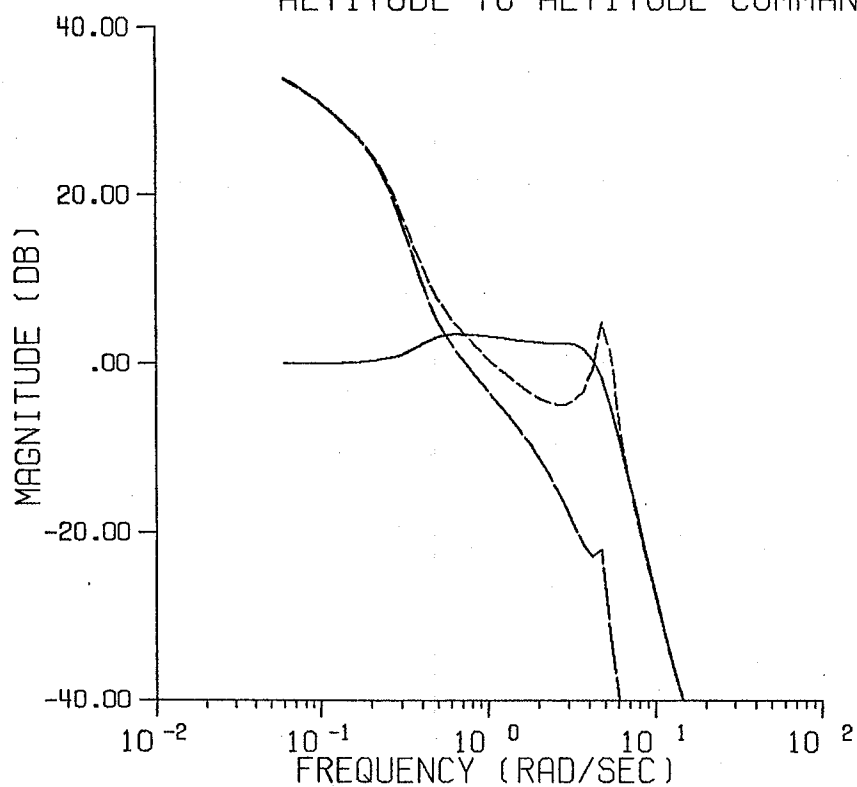


— CLOSED LOOP
- - - OPEN LOOP
- . - ALTITUDE TO STICK NO ERROR COMPENSATION

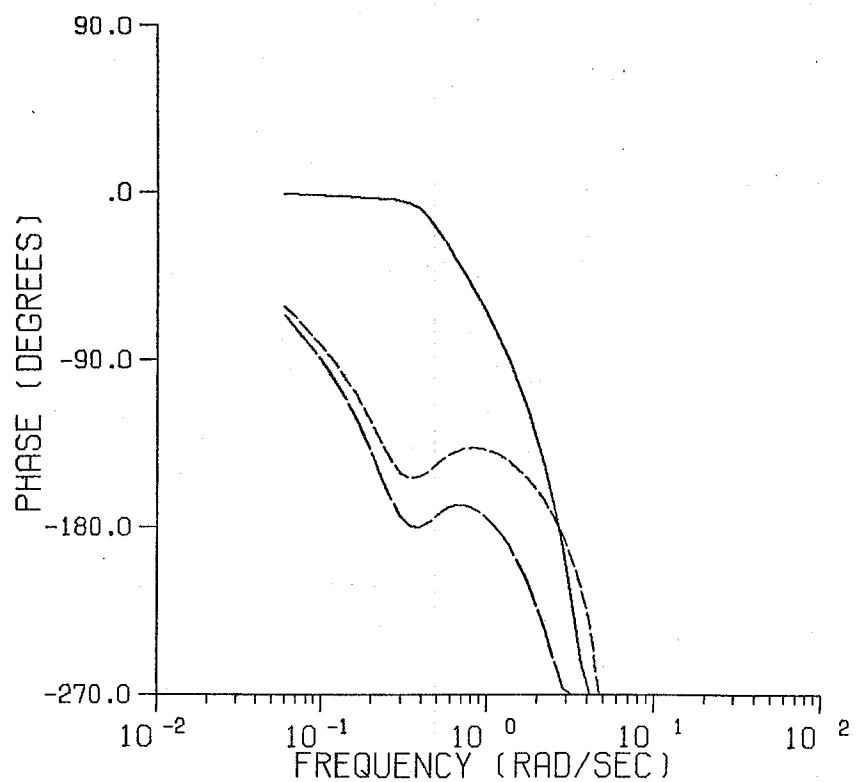


CONFIGURATION 2-2 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND

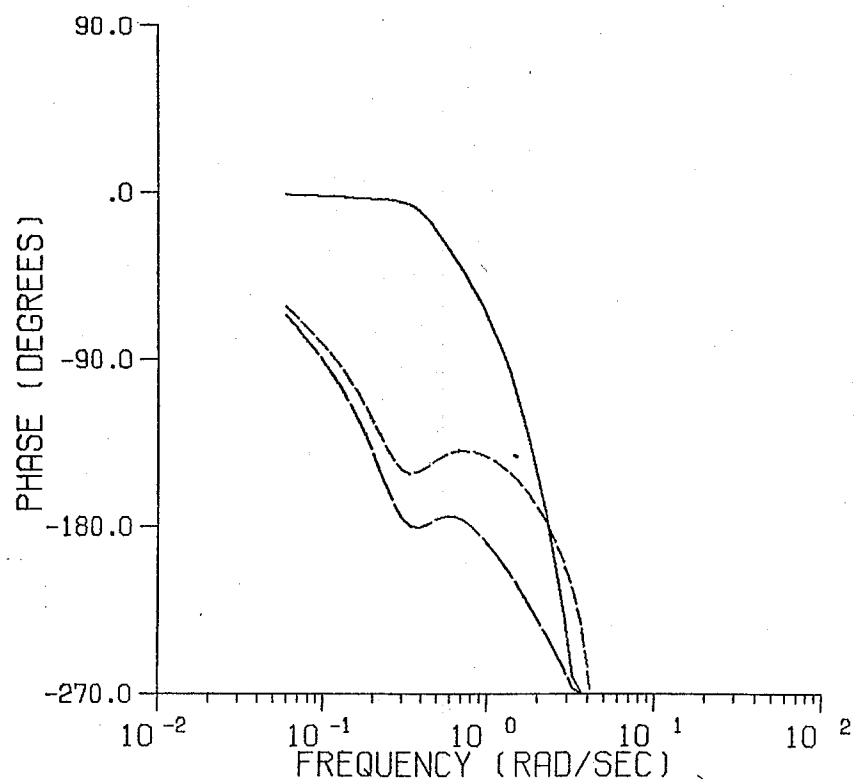
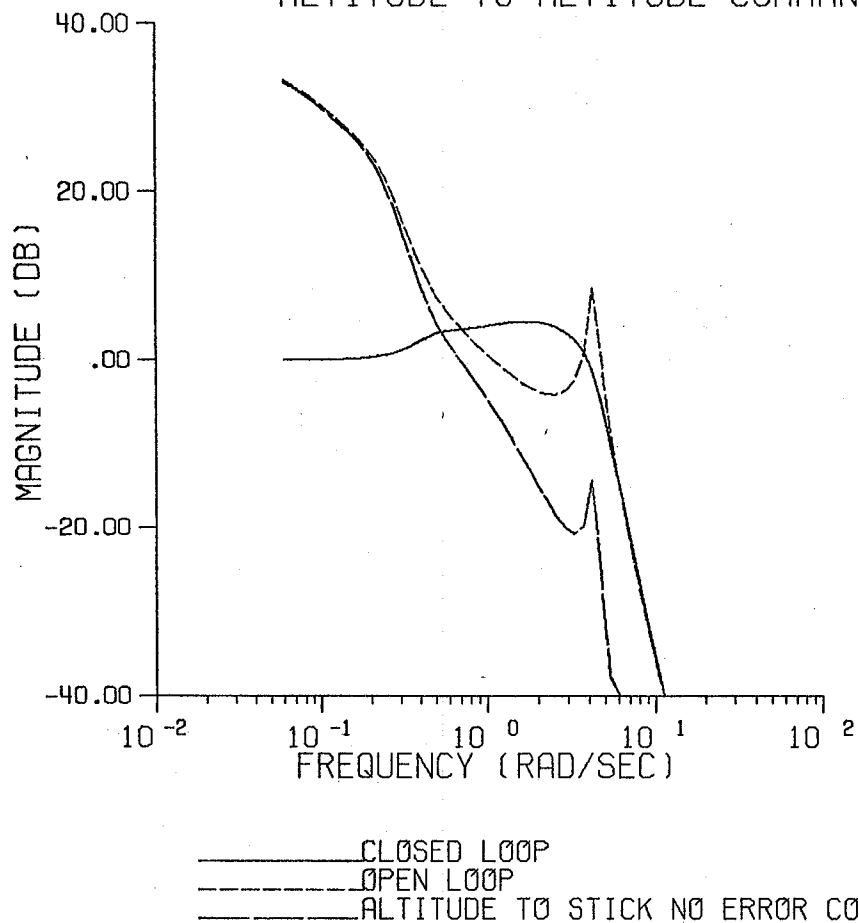


— CLOSED LOOP
- - - OPEN LOOP
- . - ALTITUDE TO STICK NO ERROR COMPENSATION



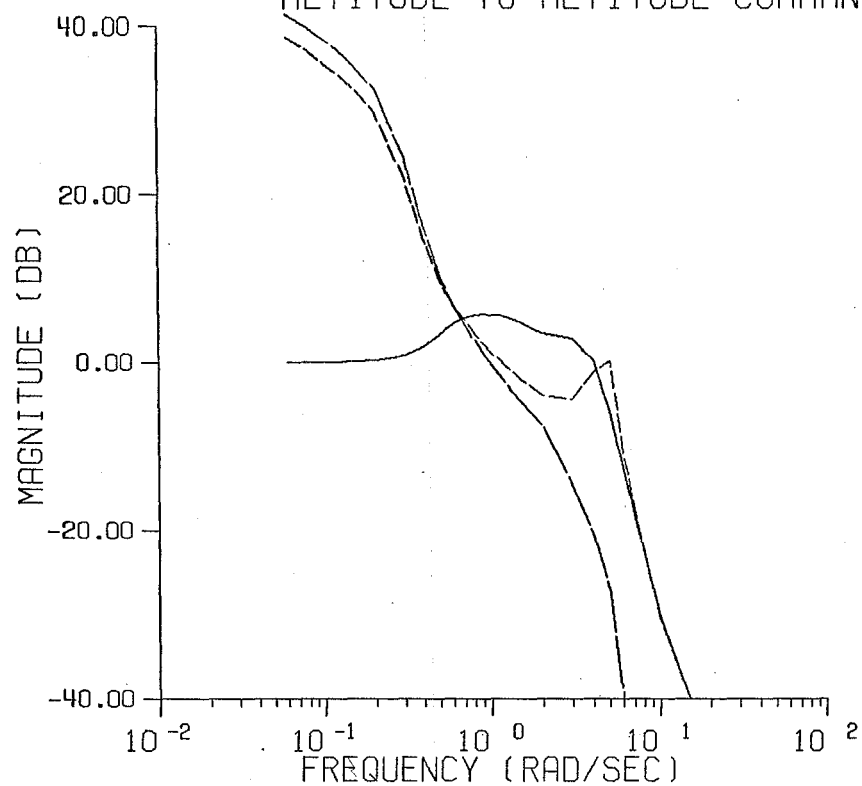
CONFIGURATION 2-3 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND

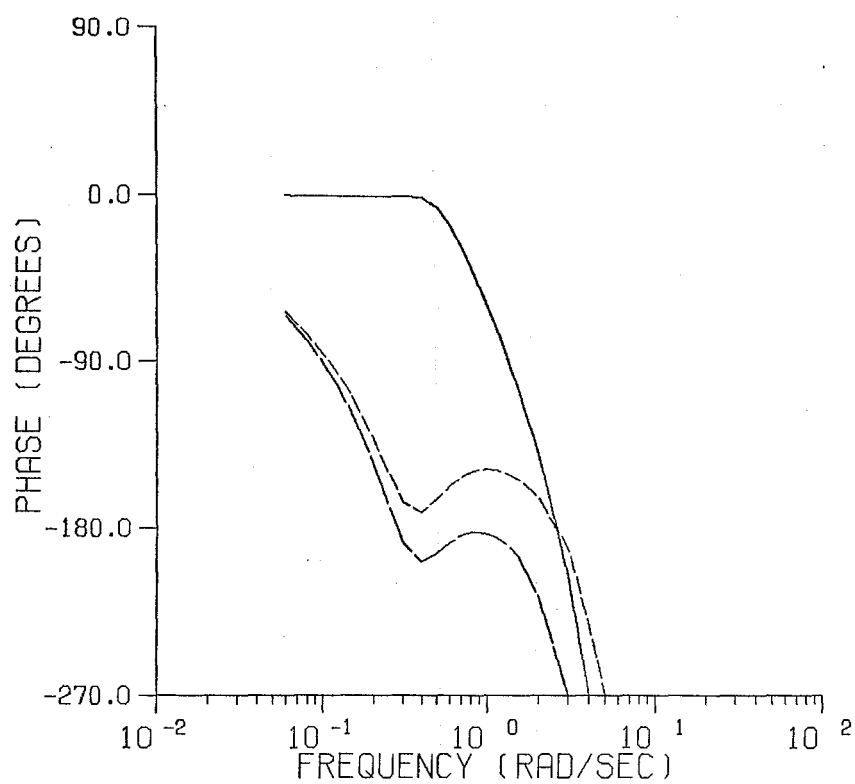


CONFIGURATION 3-1 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND

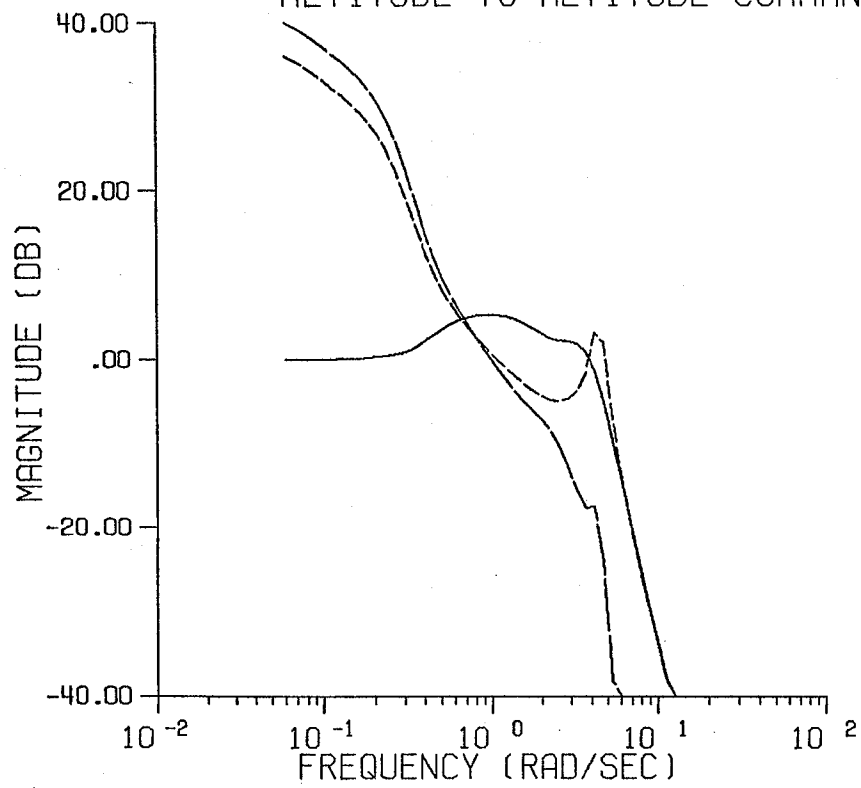


— CLOSED LOOP
- - - OPEN LOOP
- . - ALTITUDE TO STICK NO ERROR COMPENSATION

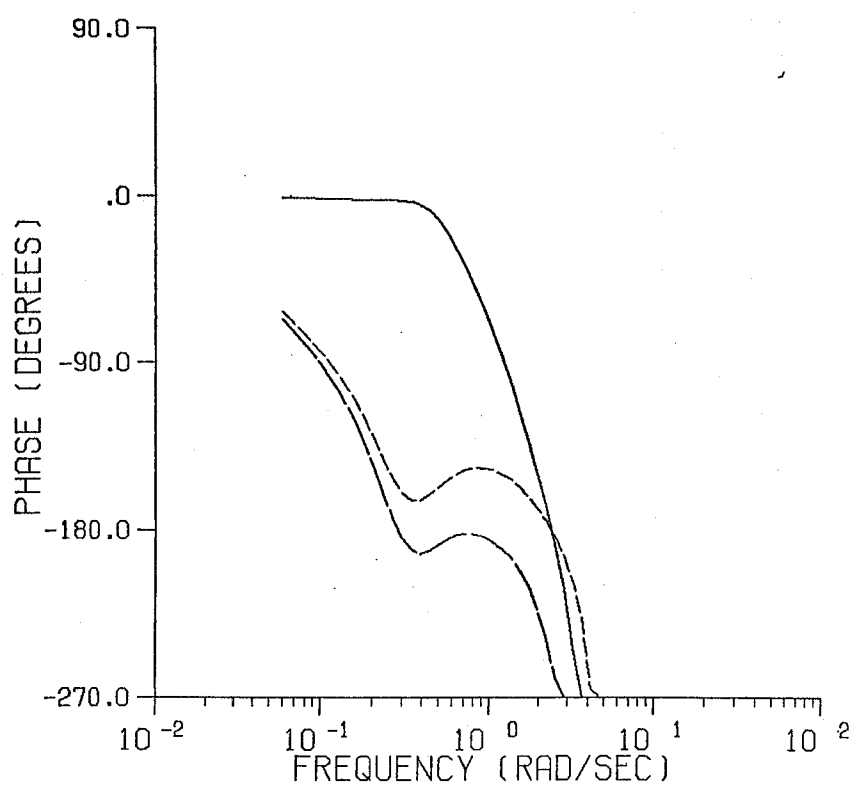


CONFIGURATION 3-2 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND

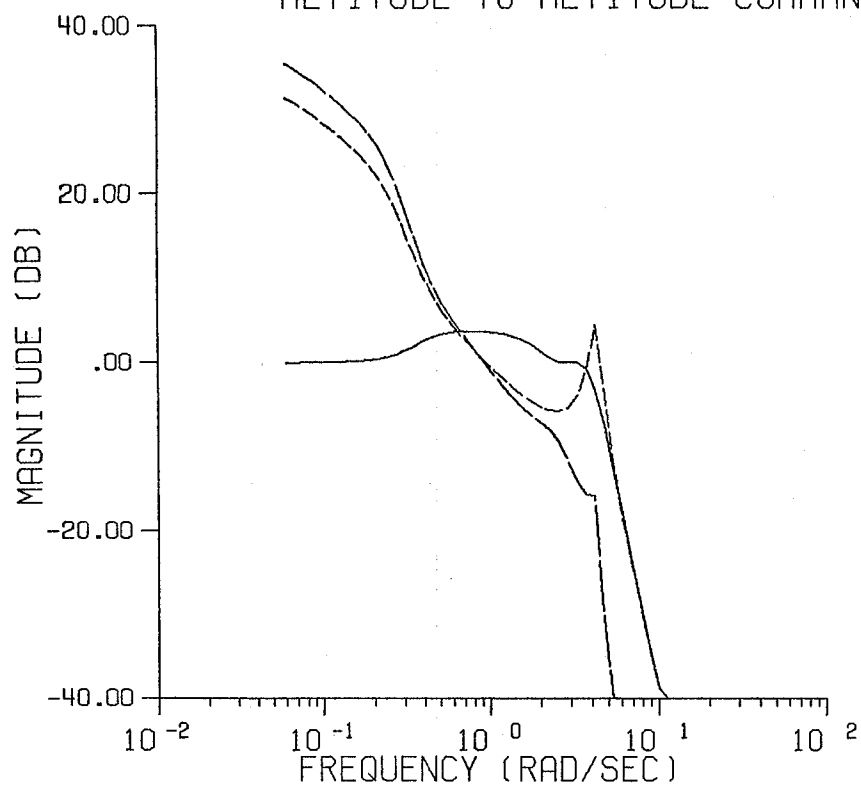


— CLOSED LOOP
- - - OPEN LOOP
- . - ALTITUDE TO STICK NO ERROR COMPENSATION

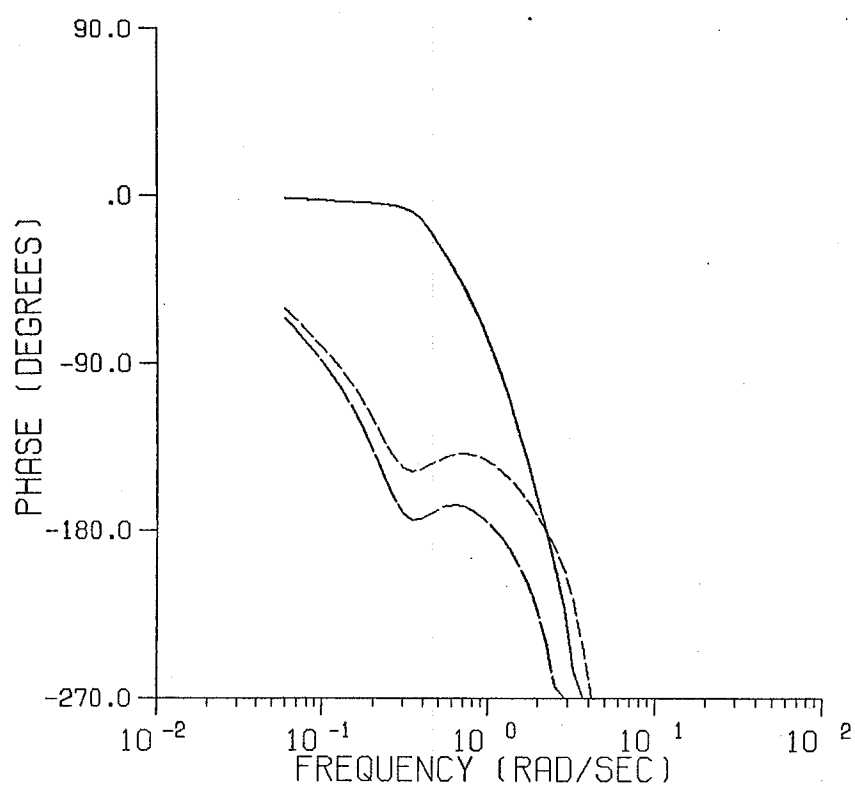


CONFIGURATION 3-3 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND

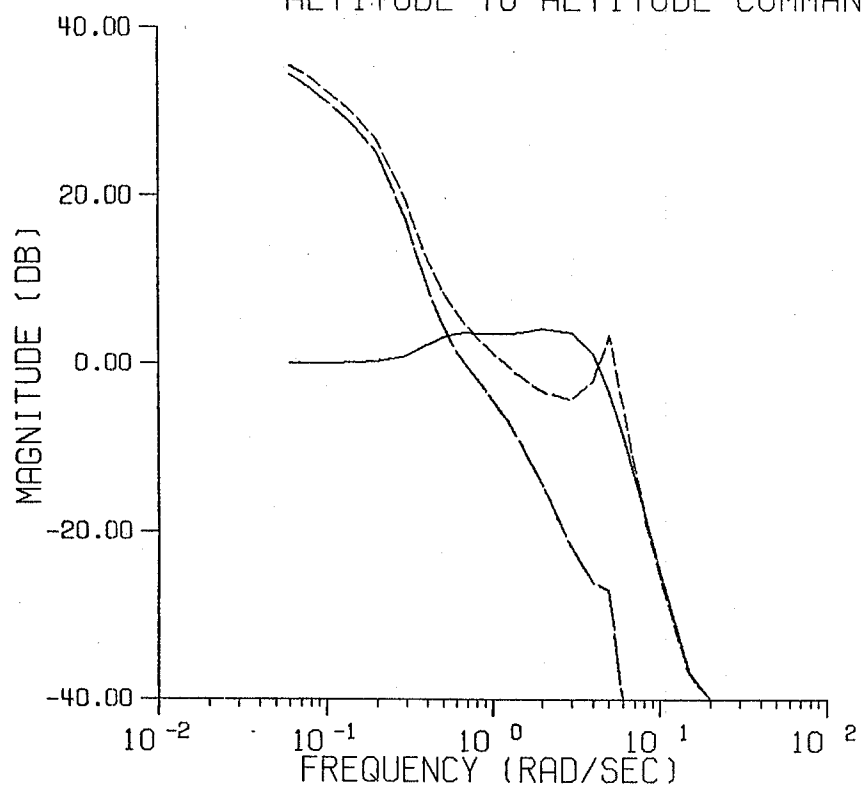


— CLOSED LOOP
- - - OPEN LOOP
- . - ALTITUDE TO STICK NO ERROR COMPENSATION

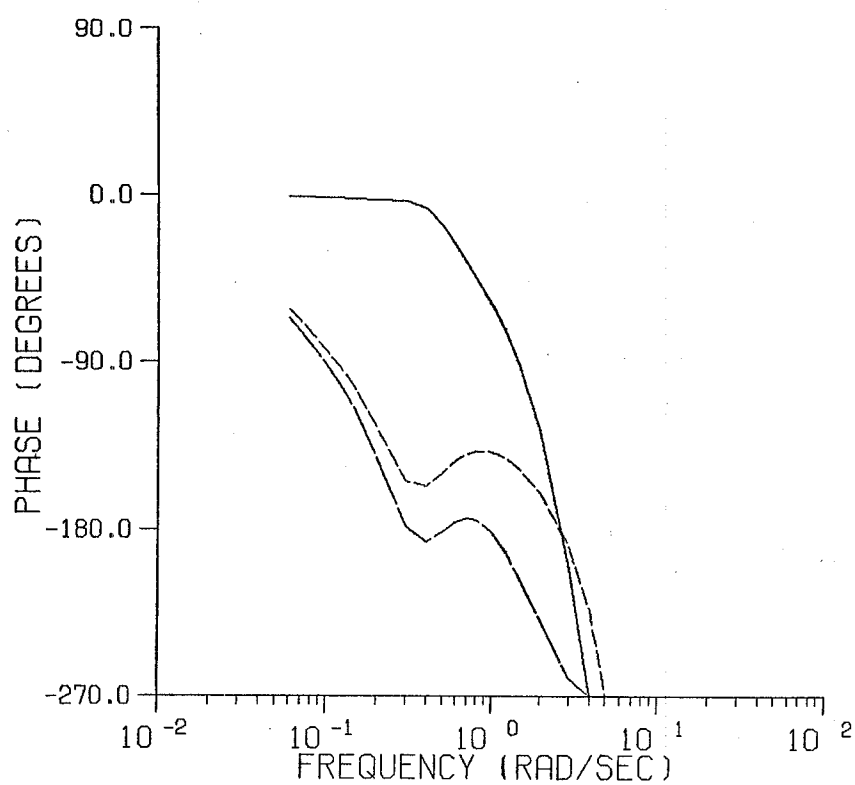


CONFIGURATION 4-1 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND

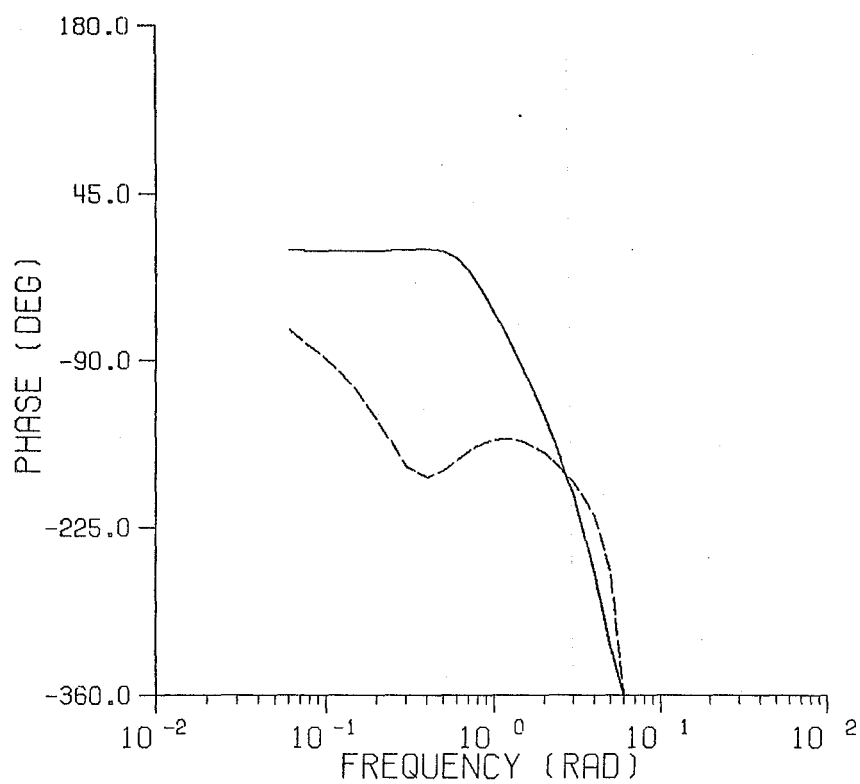
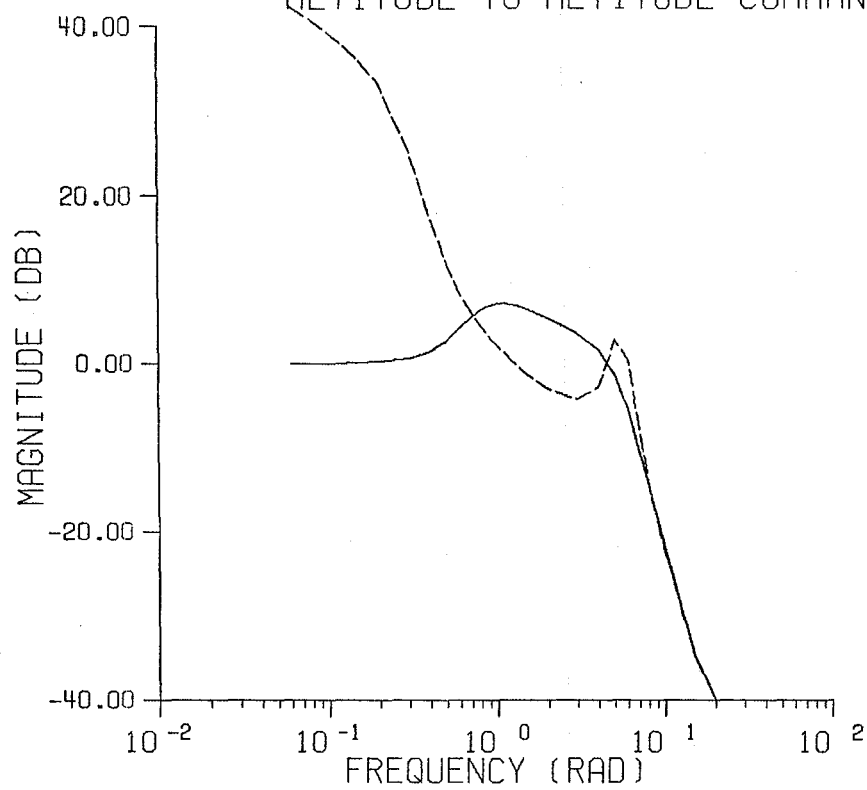


— CLOSED LOOP
- - - OPEN LOOP
- . - ALTITUDE TO STICK NO ERROR COMPENSATION



CONFIGURATION 5-1 ALTITUDE TRACKING

ALTITUDE TO ALTITUDE COMMAND



These plots show the effect of each of the pilots feed backs on the closed loop frequency response. i.e. It is an 'inside loop' out type of design showing

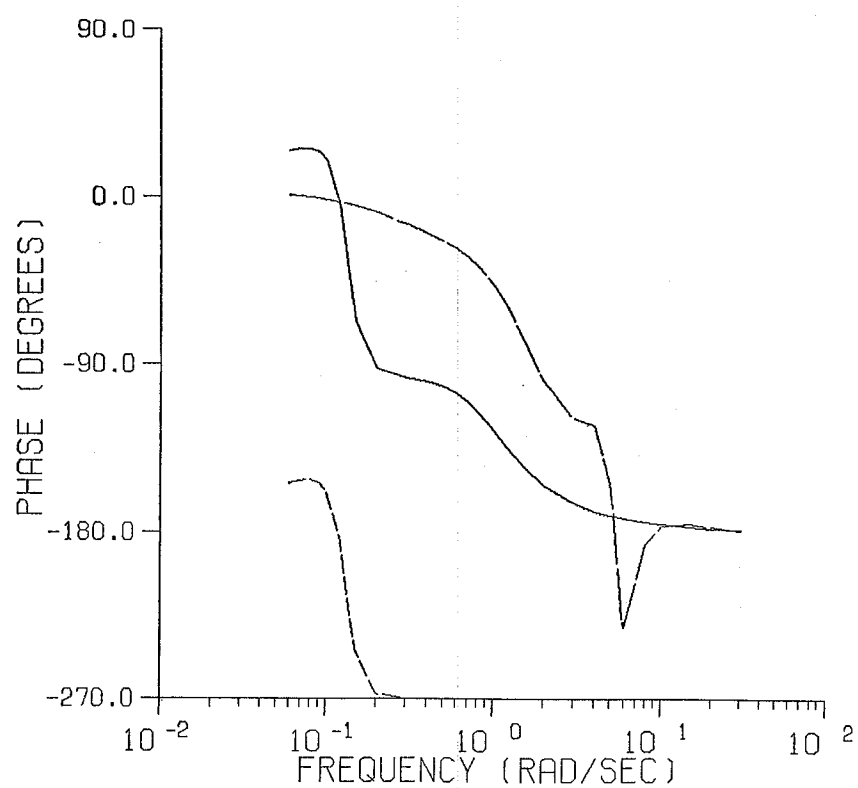
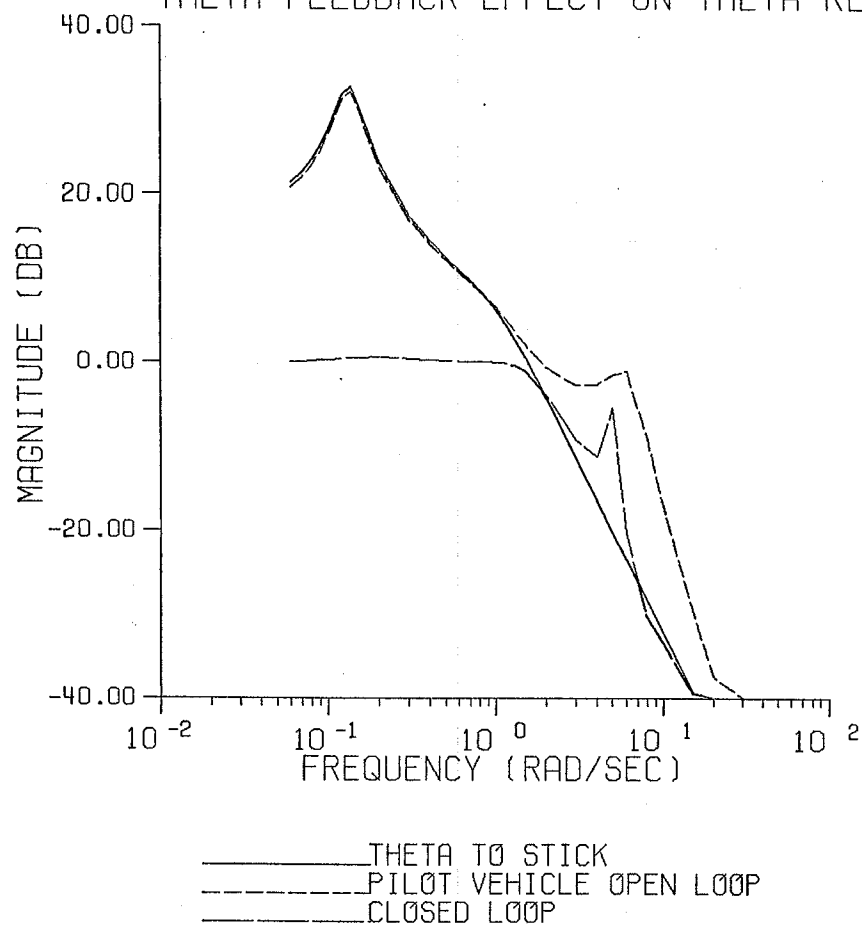
- ① The effect of θ feedback on the theta to stick response
- ② The effect of altitude feedback on altitude to stick response (with the inner theta loop closed)
- ③ The effect of the feedforward pilot response to altitude error block on the open and finally closed loop frequency responses.

Note: ① On the 'theta feedback effect...' plots closed loop is theta to stick with the pilots θ feedback loop closed.

② The #3 above is shown on the 'altitude to altitude command plots.' 'Altitude to stick no error comp' is all inner loops closed with no pilot response to altitude error block included. 'Open loop' is then with this included.

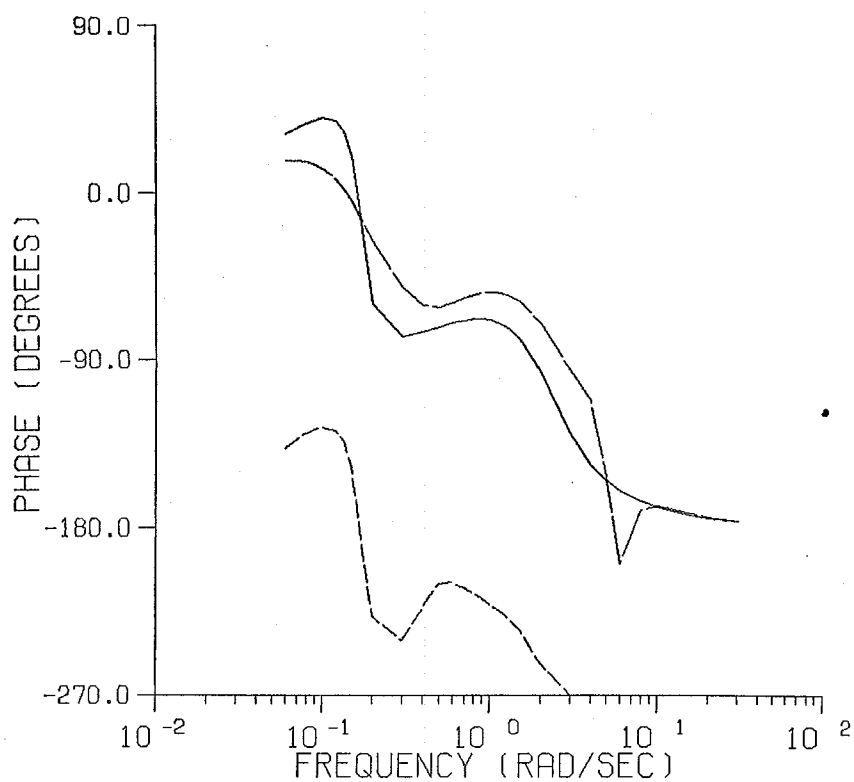
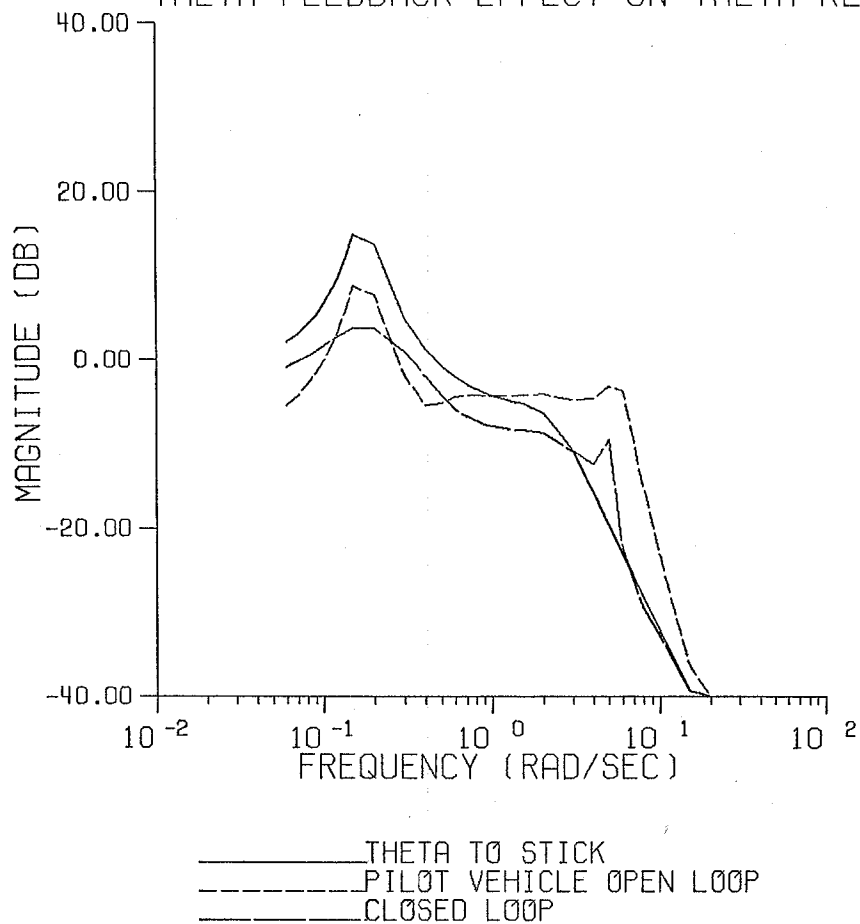
CONFIGURATION 1-1 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE

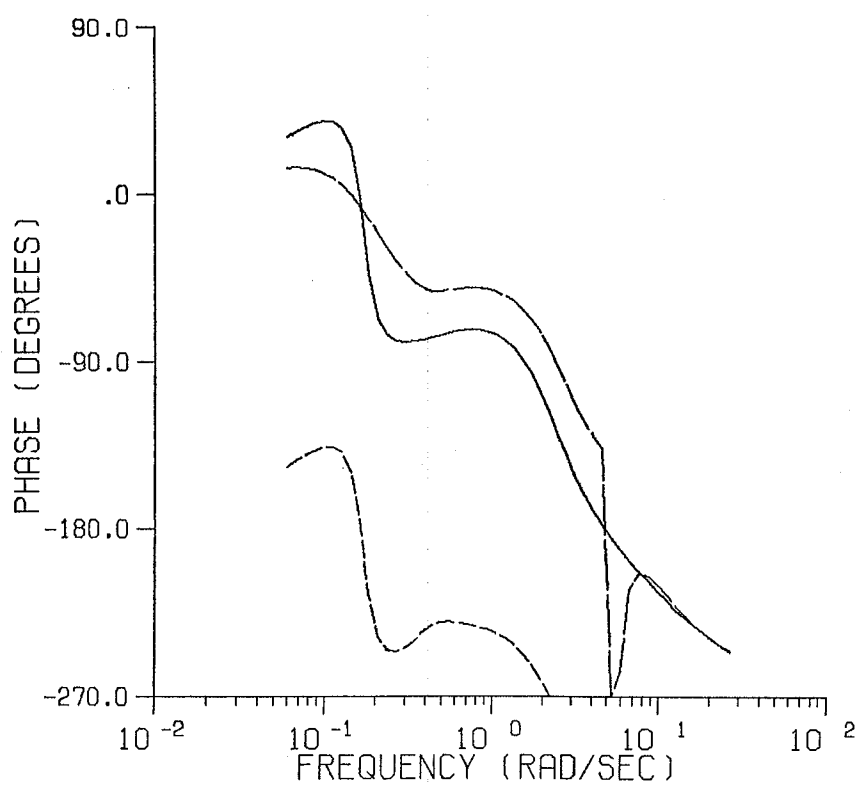
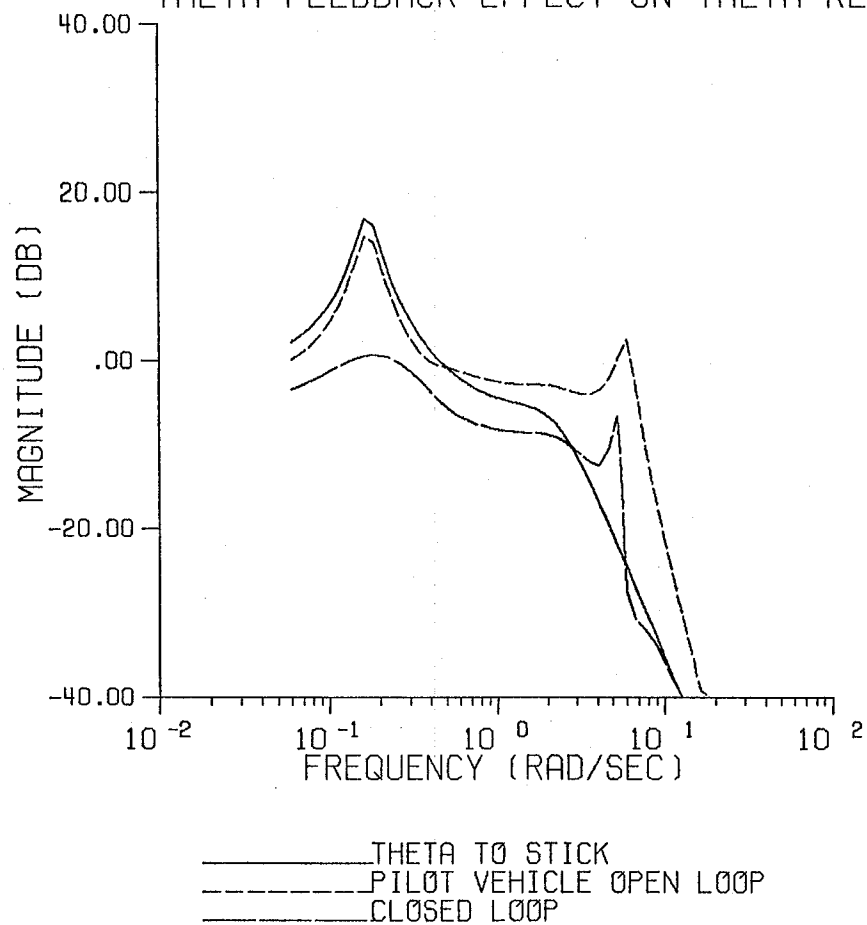


CONFIGURATION 2-1 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE

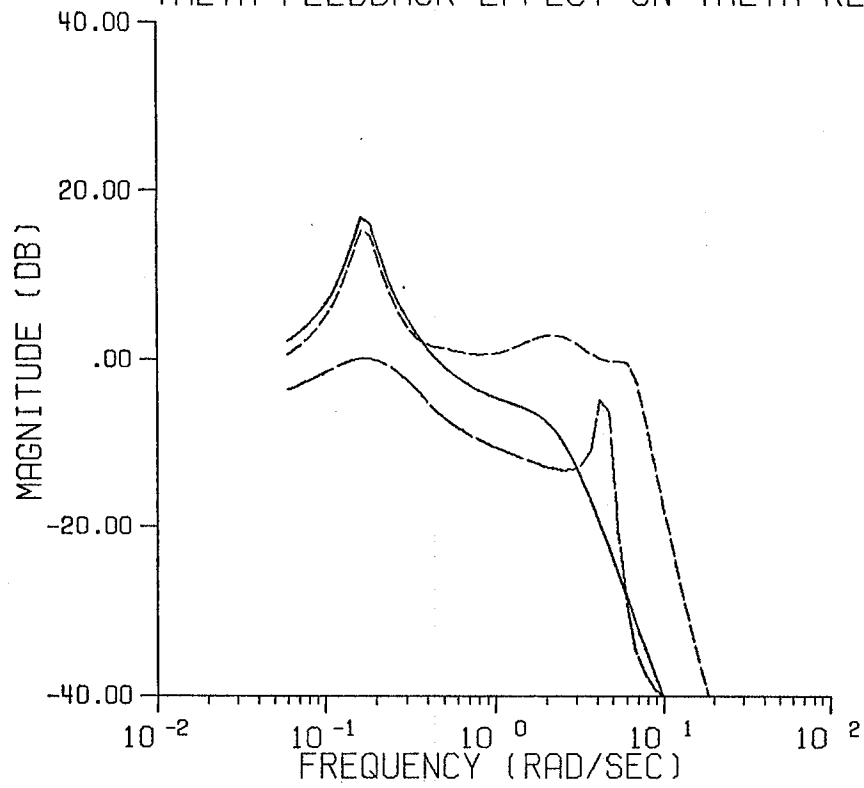


CONFIGURATION 2-2 ALTITUDE TRACKING
THETA FEEDBACK EFFECT ON THETA RESPONSE

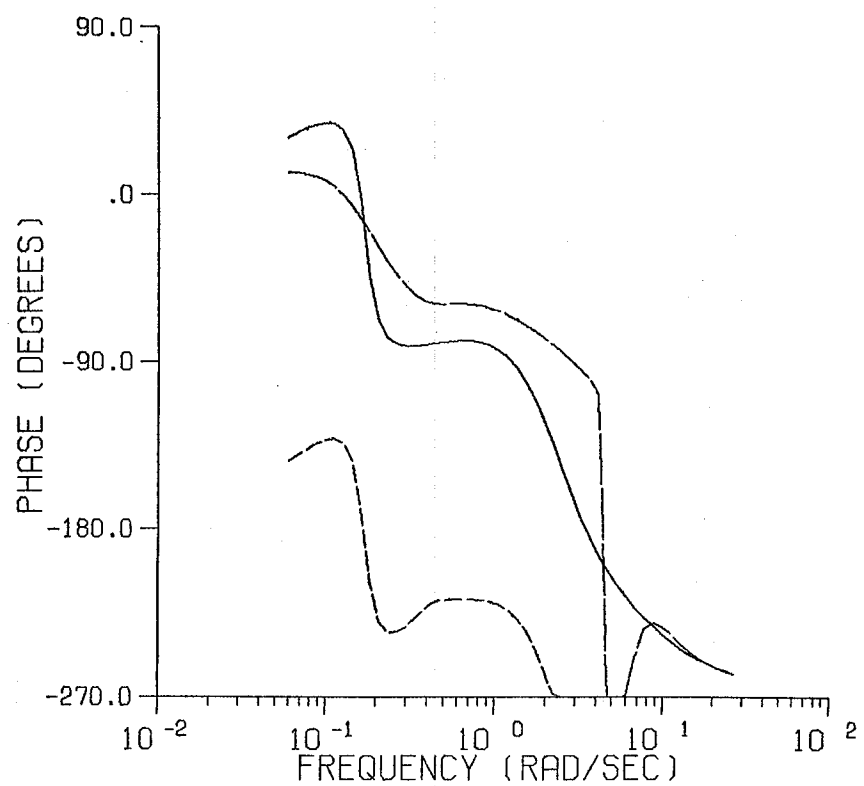


CONFIGURATION 2-3 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE

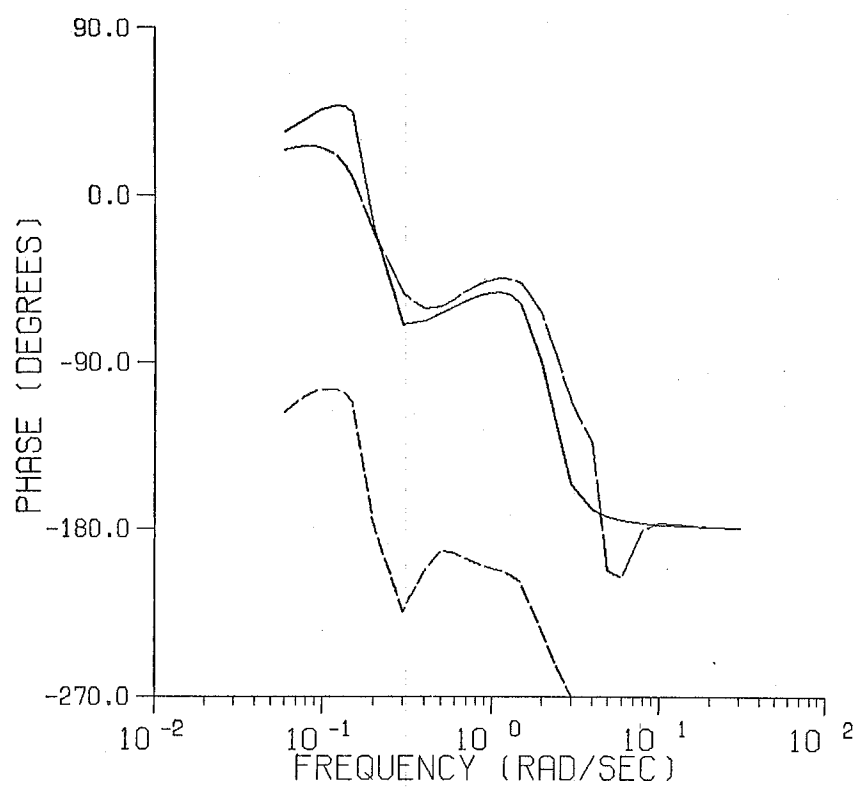
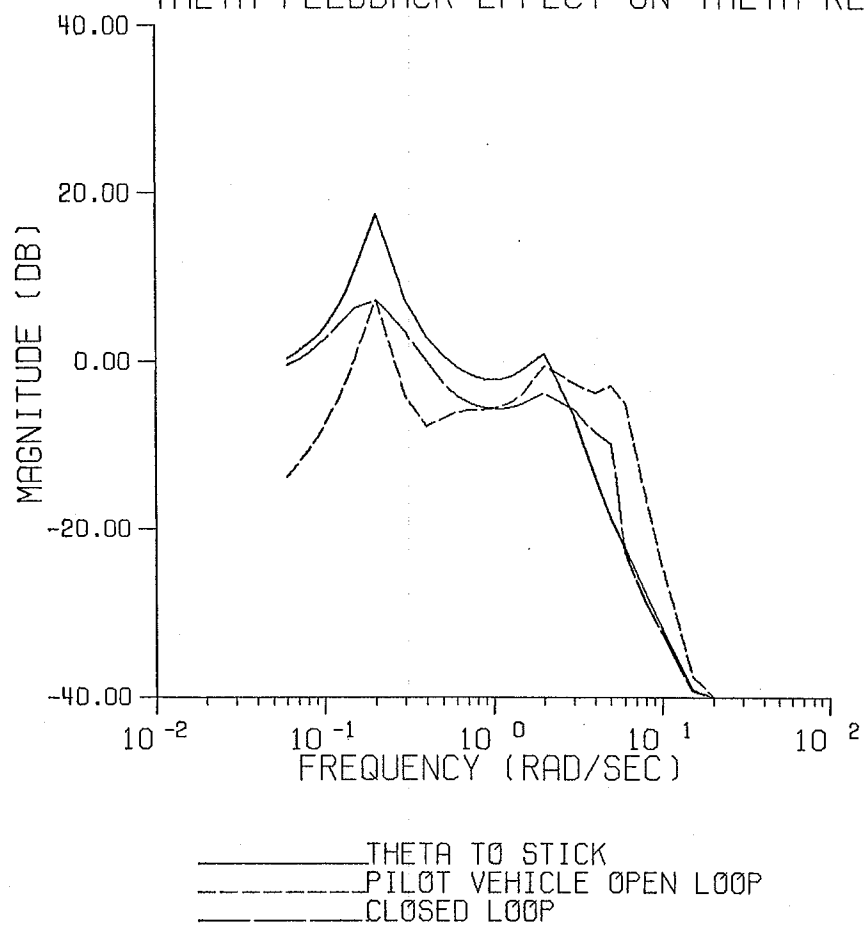


— THETA TO STICK
- - - PILOT VEHICLE OPEN LOOP
- . - CLOSED LOOP



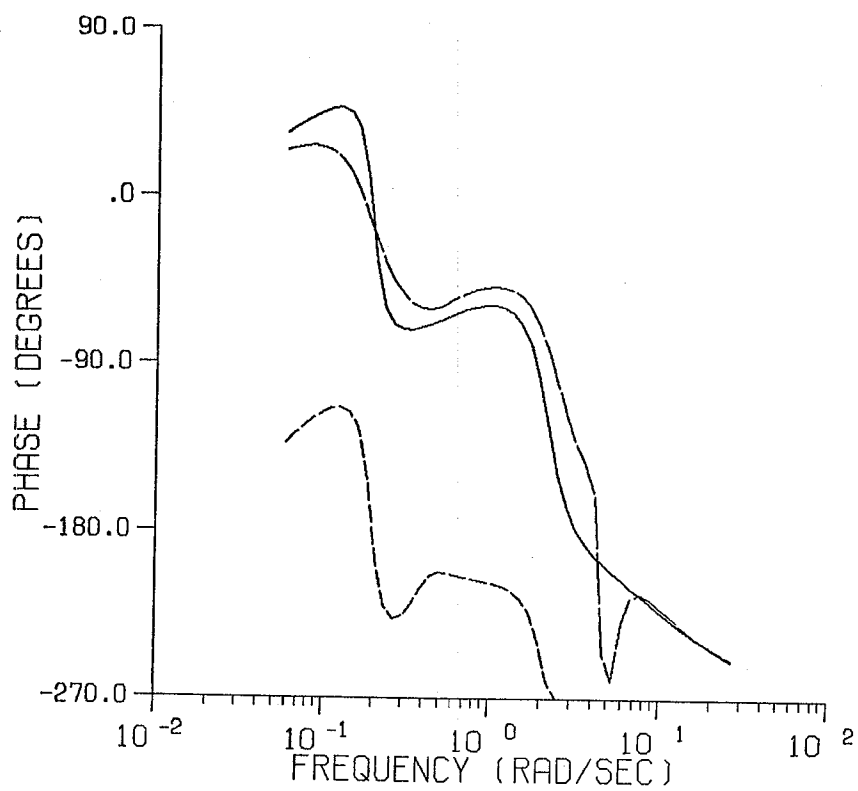
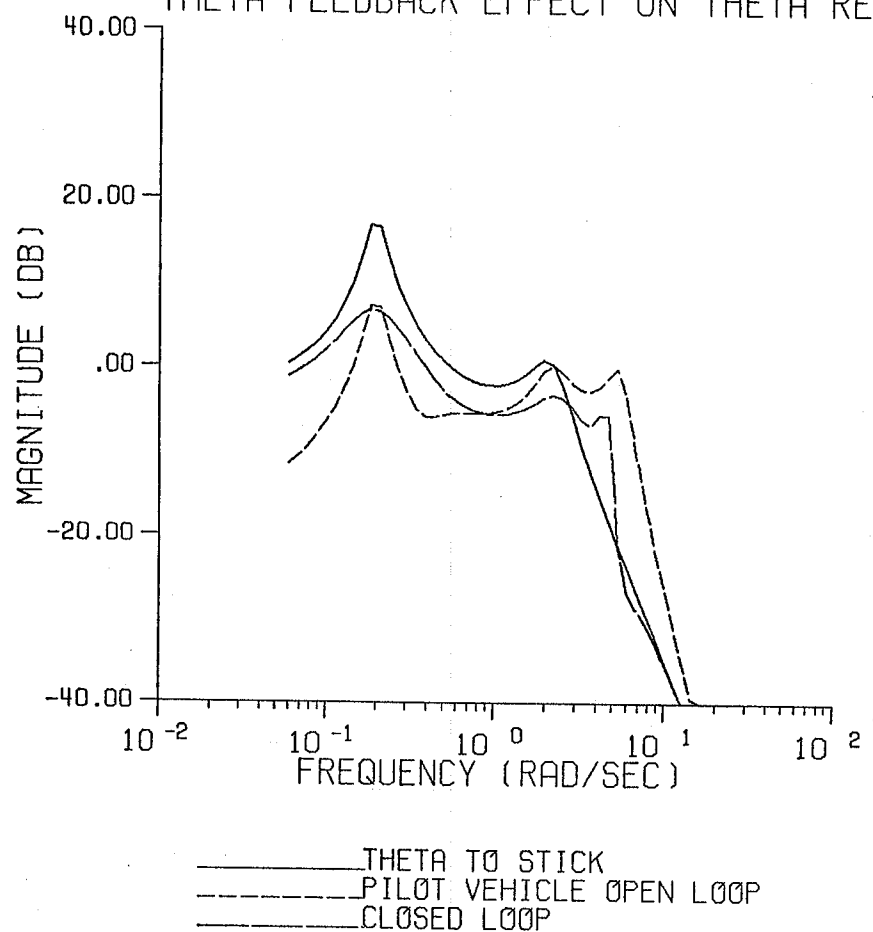
CONFIGURATION 3-1 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE



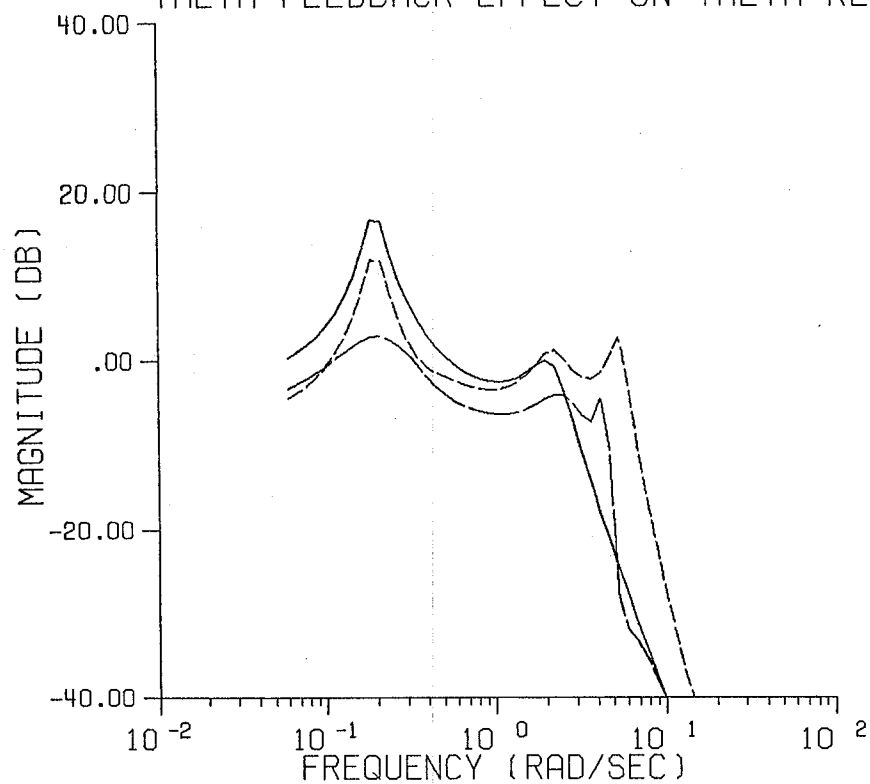
CONFIGURATION 3-2 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE

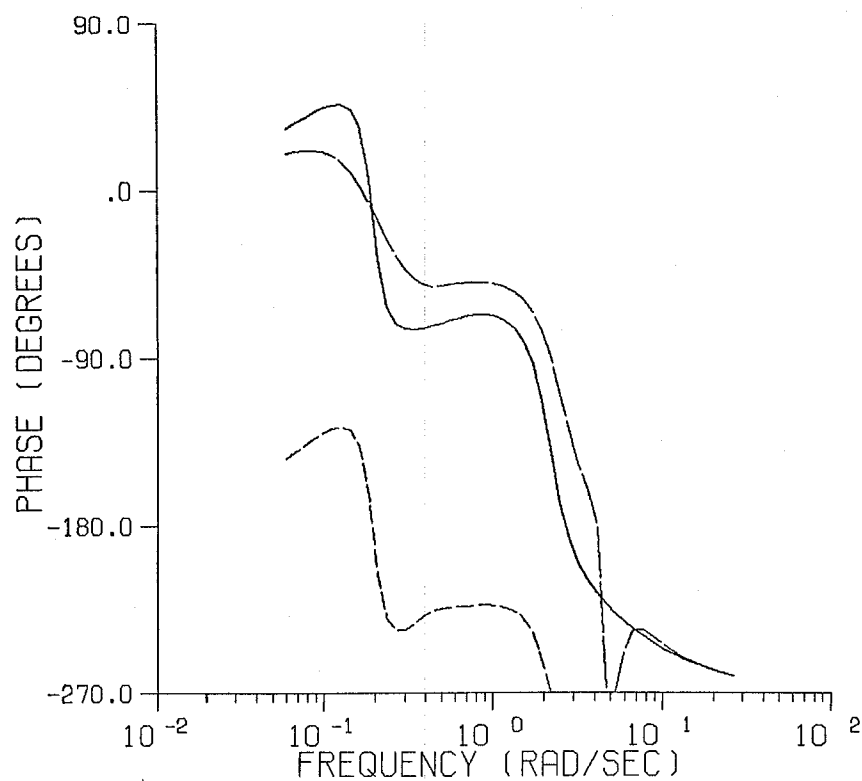


CONFIGURATION 3-3 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE

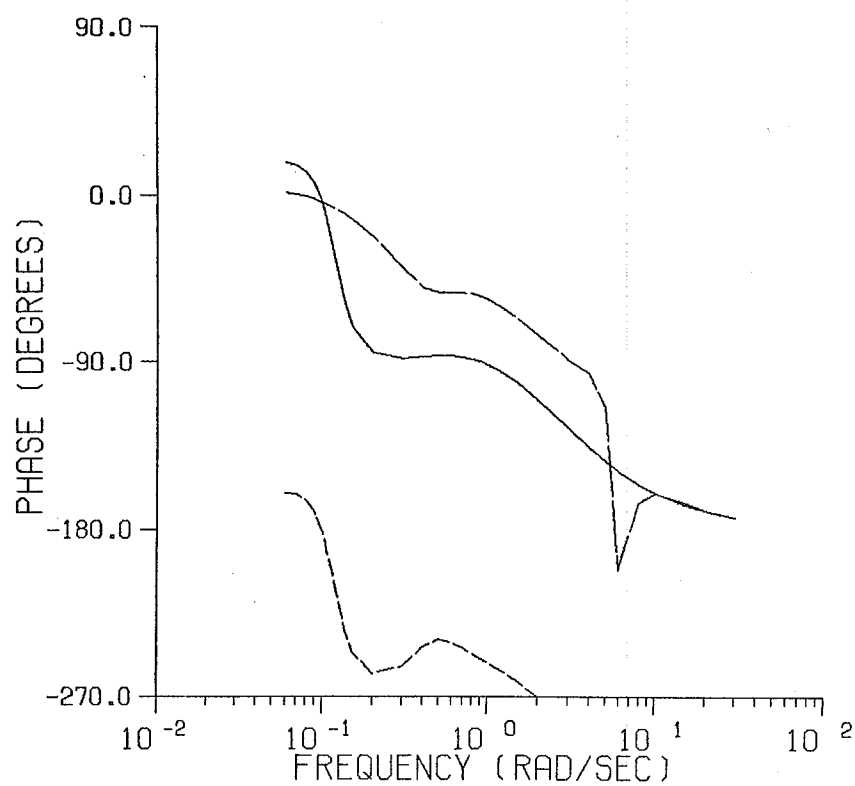
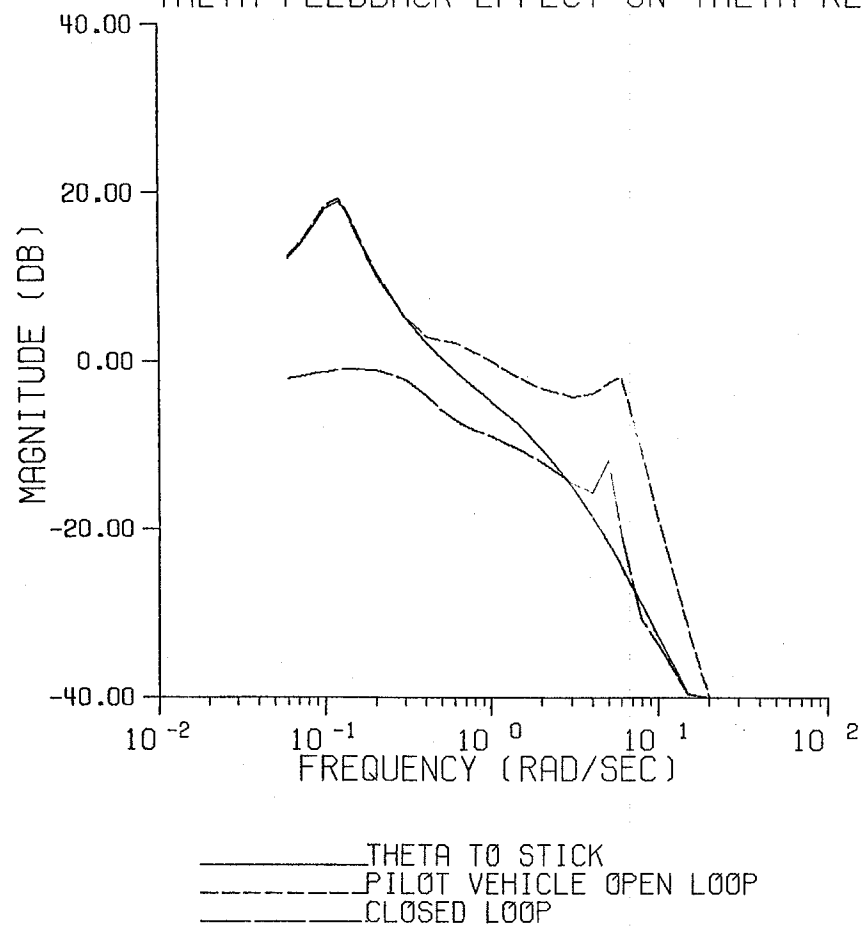


— THETA TO STICK
- - - PILOT VEHICLE OPEN LOOP
- . - CLOSED LOOP



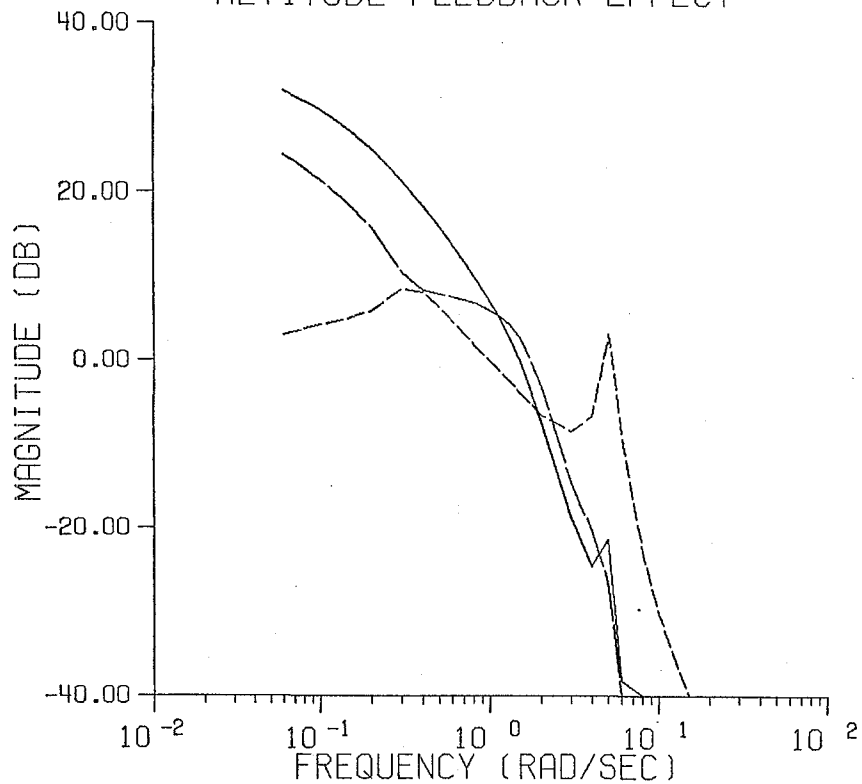
CONFIGURATION 4-1 ALTITUDE TRACKING

THETA FEEDBACK EFFECT ON THETA RESPONSE

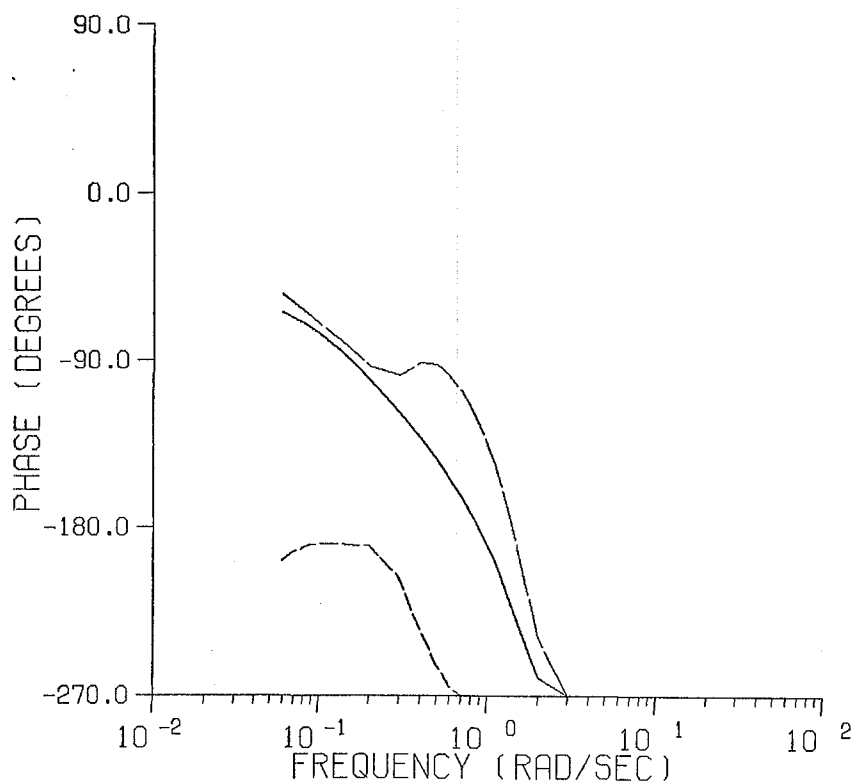


CONFIGURATION 1-1 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

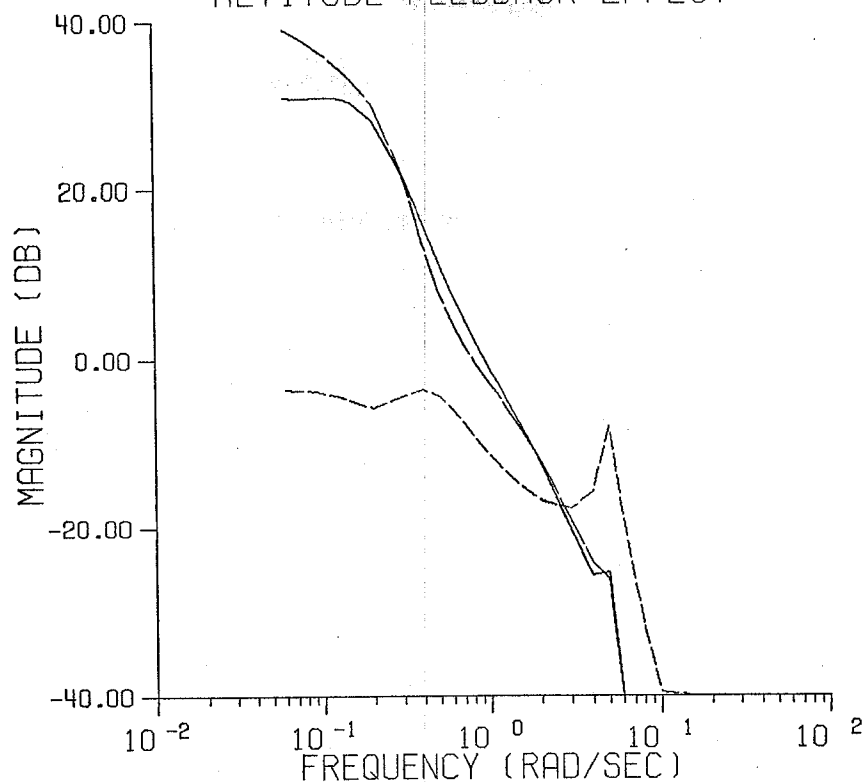


—— ALTITUDE TO STICK WITH THETA FEEDBACK
----- OPEN LOOP PILOT VEHICLE
- . - . - . CLOSED LOOP ALTITUDE TO STICK

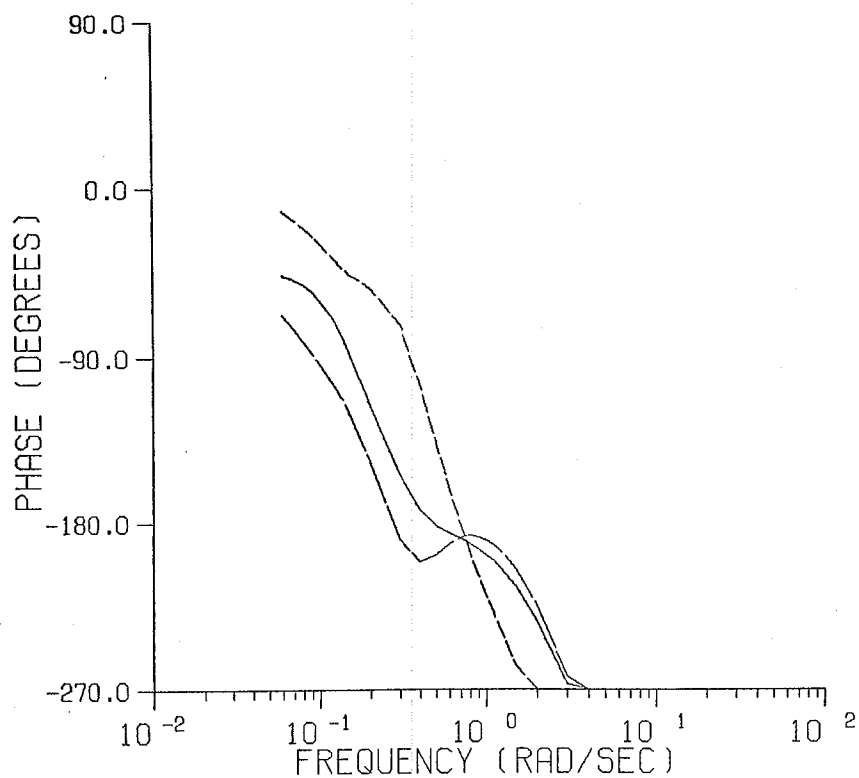


CONFIGURATION 2-1 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

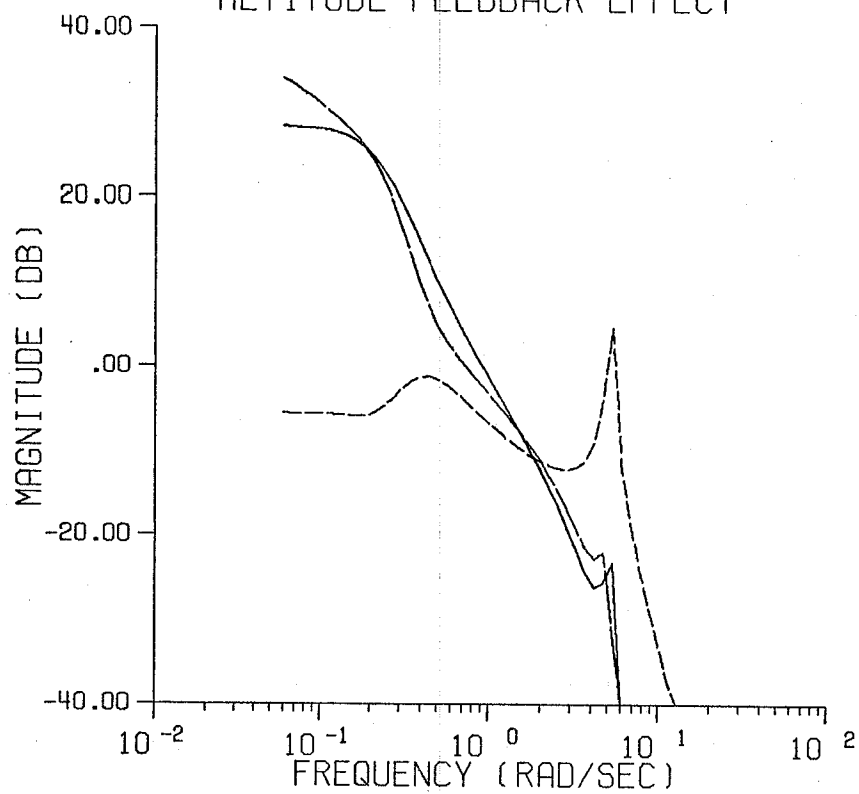


— ALTITUDE TO STICK WITH THETA FEEDBACK
- - - OPEN LOOP PILOT VEHICLE
- . - - CLOSED LOOP ALTITUDE TO STICK

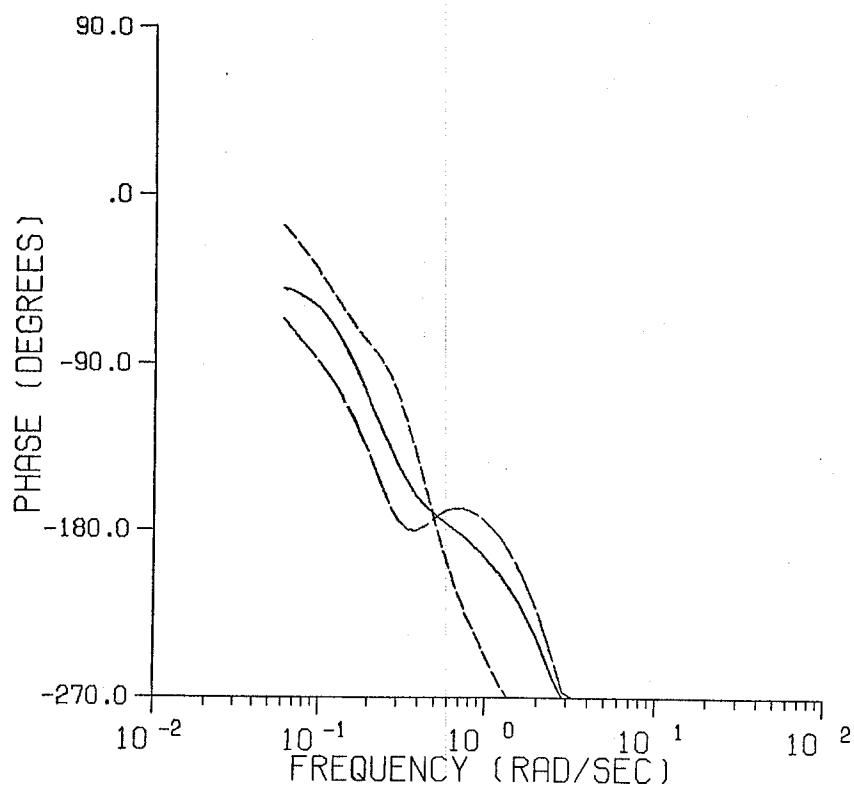


CONFIGURATION 2-2 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

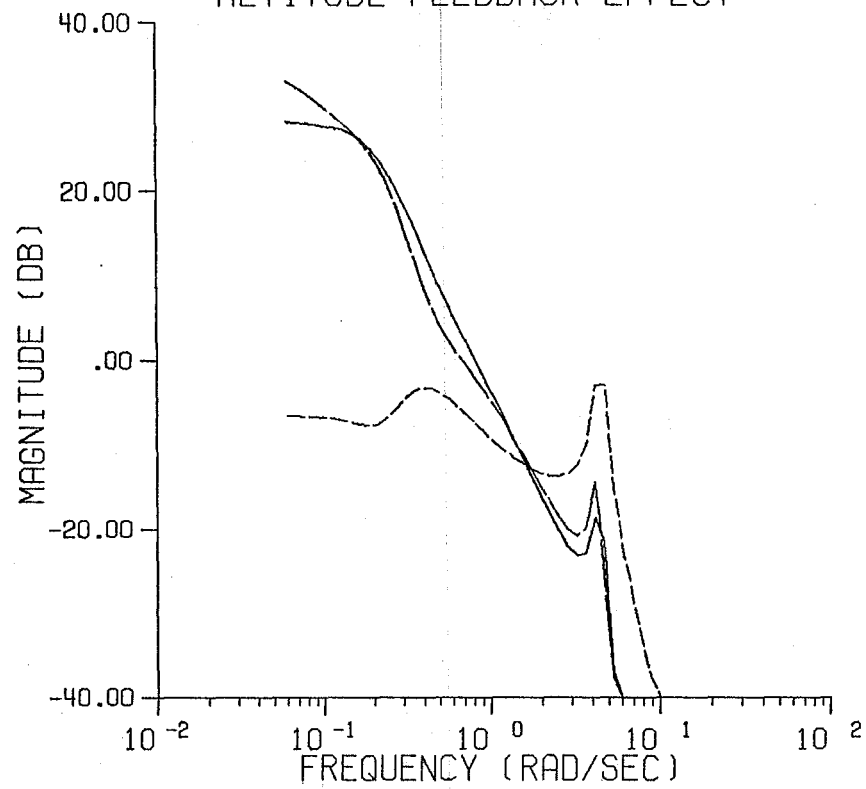


— ALTITUDE TO STICK WITH THETA FEEDBACK
--- OPEN LOOP PILOT VEHICLE
-.- CLOSED LOOP ALTITUDE TO STICK

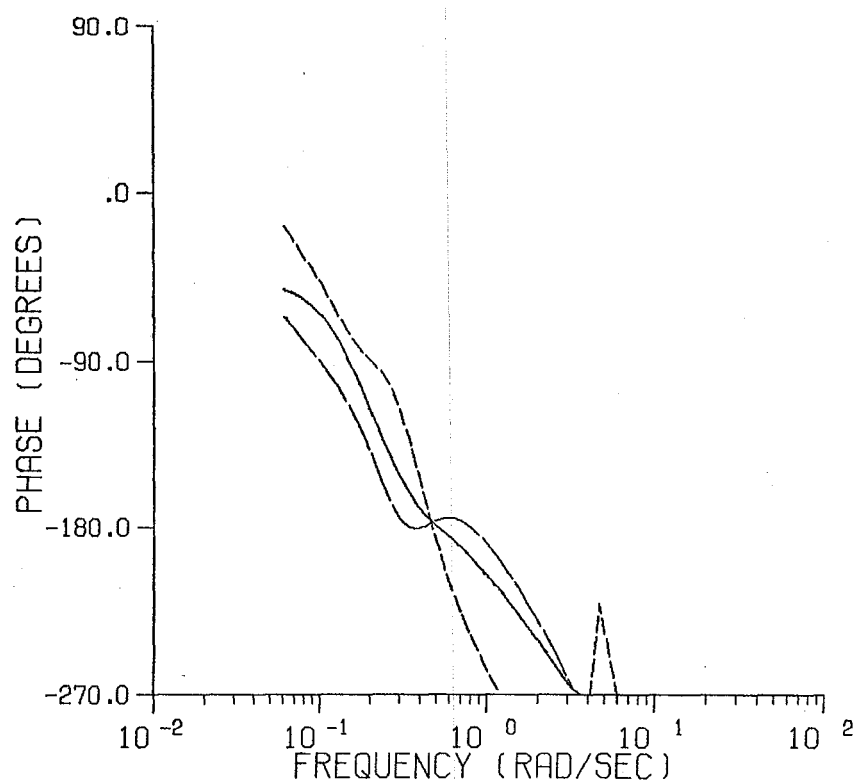


CONFIGURATION 2-3 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

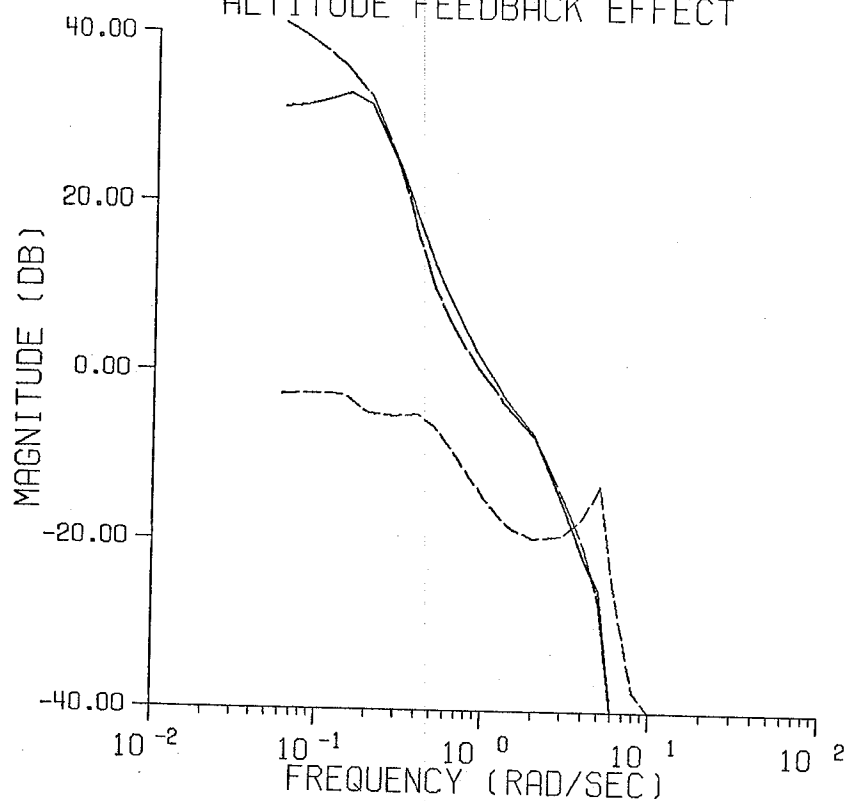


— ALTITUDE TO STICK WITH THETA FEEDBACK
--- OPEN LOOP PILOT VEHICLE
— CLOSED LOOP ALTITUDE TO STICK

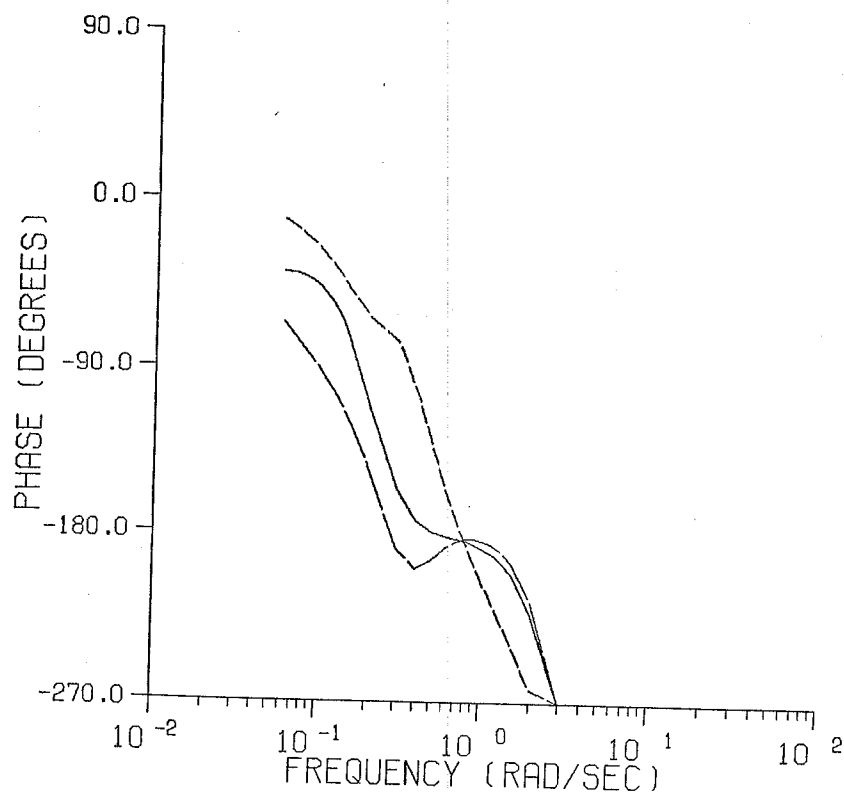


CONFIGURATION 3-1 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

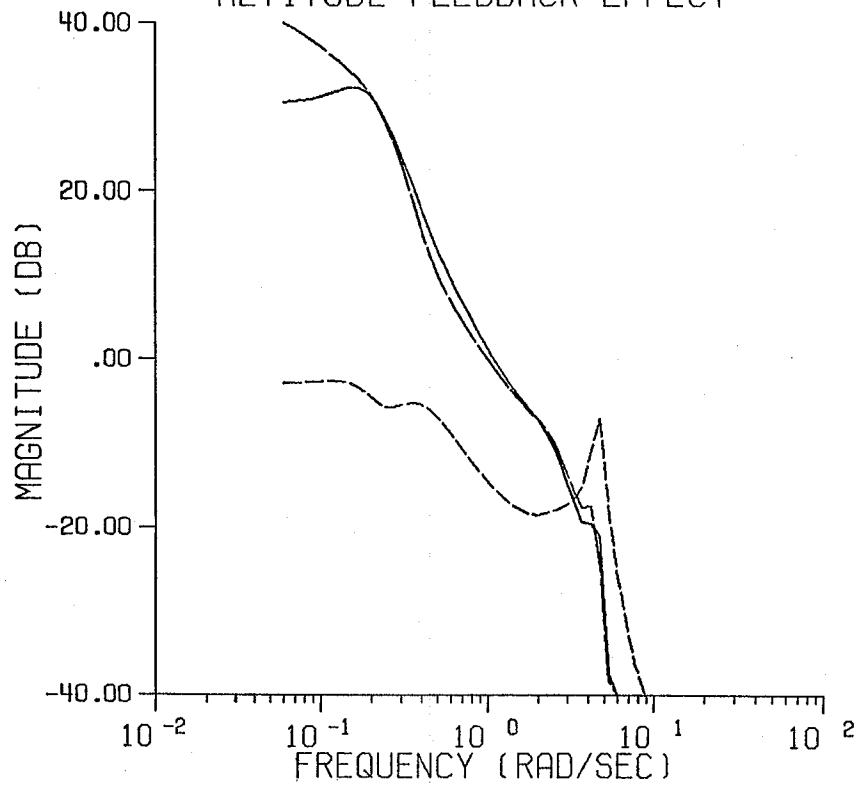


— ALTITUDE TO STICK WITH THETA FEEDBACK
- - - OPEN LOOP PILOT VEHICLE
- . - CLOSED LOOP ALTITUDE TO STICK

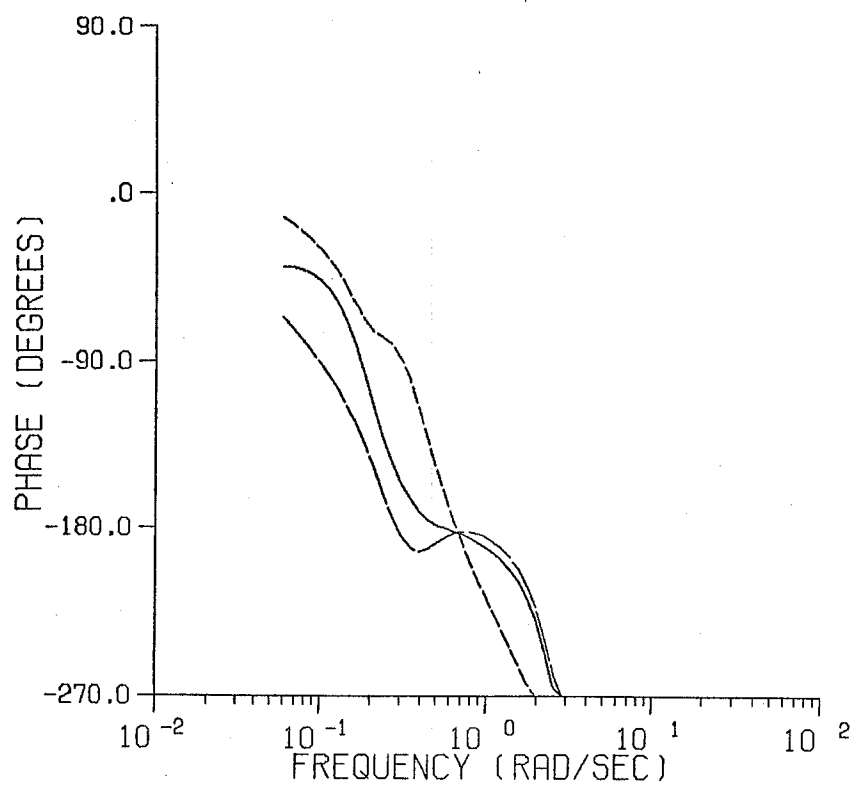


CONFIGURATION 3-2 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

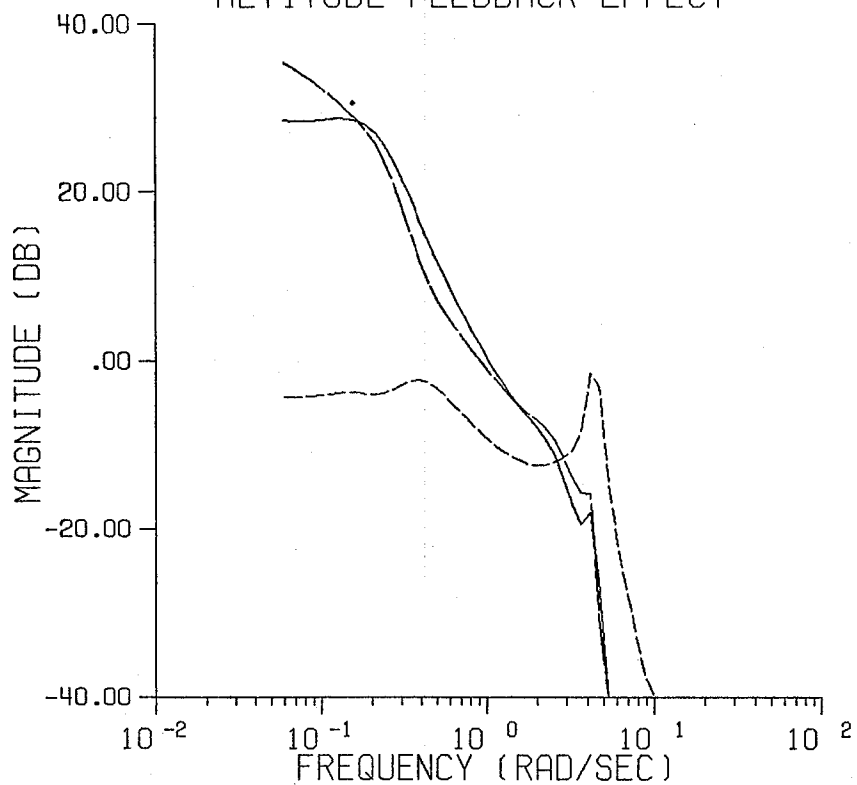


— ALTITUDE TO STICK WITH THETA FEEDBACK
- - - OPEN LOOP PILOT VEHICLE
- . - CLOSED LOOP ALTITUDE TO STICK

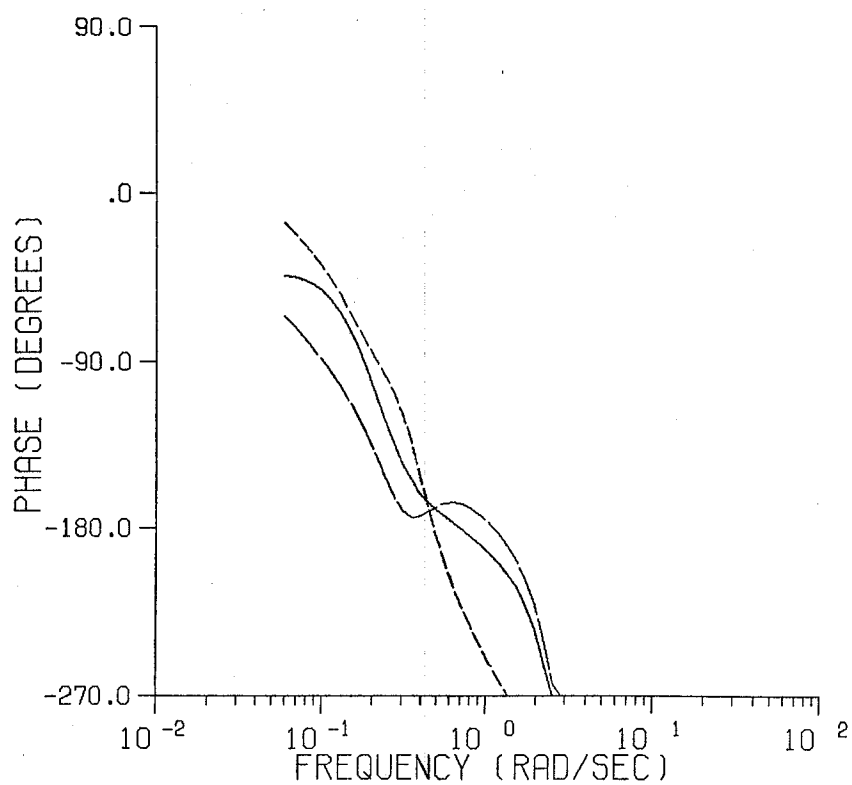


CONFIGURATION 3-3 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT

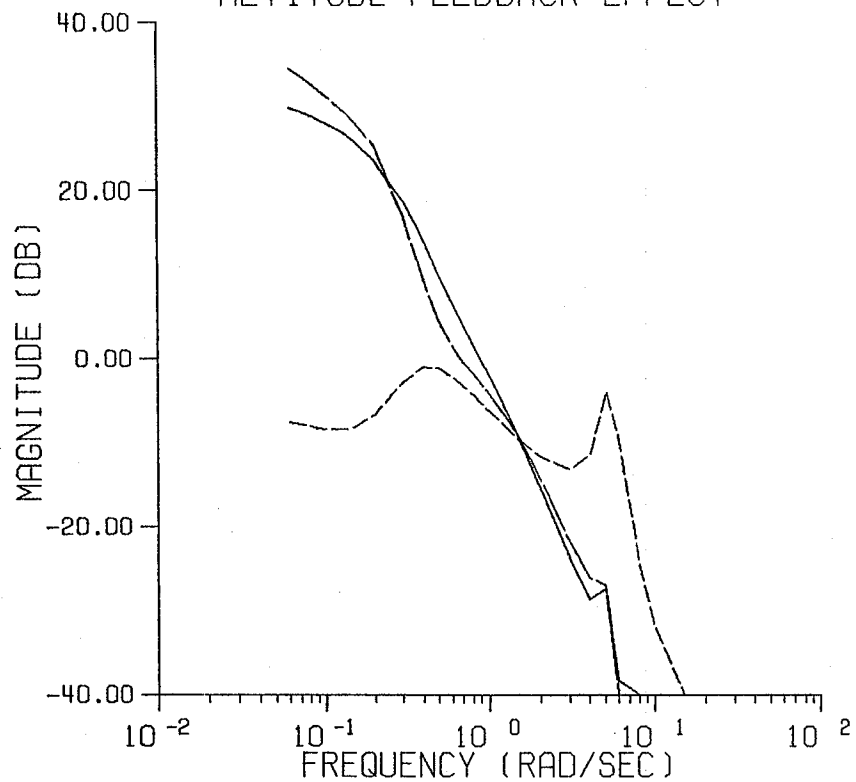


— ALTITUDE TO STICK WITH THETA FEEDBACK
- - - OPEN LOOP PILOT VEHICLE
- . - CLOSED LOOP ALTITUDE TO STICK

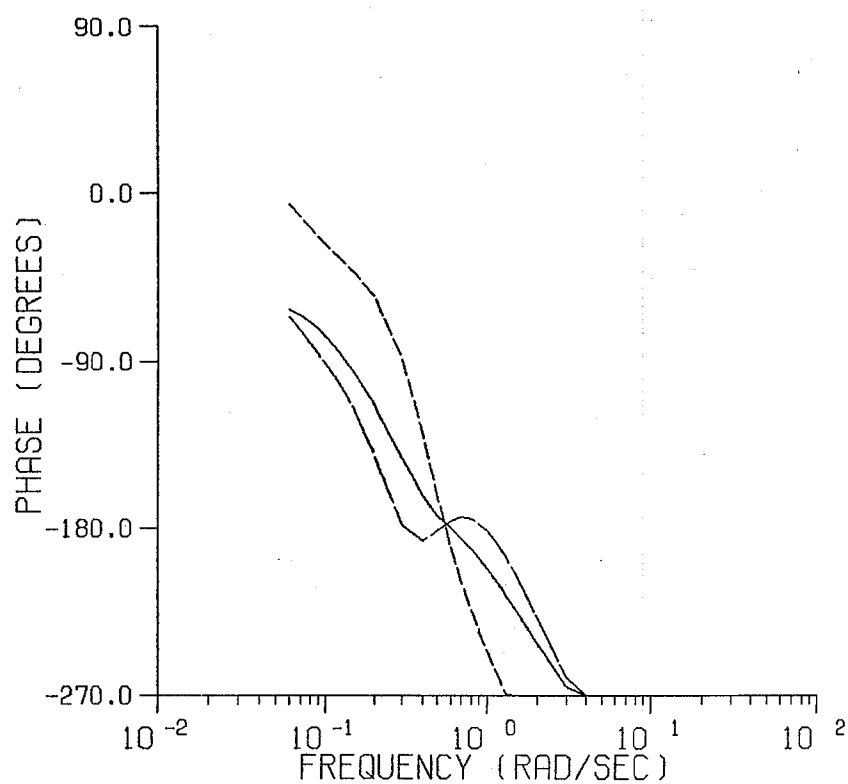


CONFIGURATION 4-1 ALTITUDE TRACKING

ALTITUDE FEEDBACK EFFECT



— ALTITUDE TO STICK WITH THETA FEEDBACK
- - - OPEN LOOP PILOT VEHICLE
- . - CLOSED LOOP ALTITUDE TO STICK



These plots are the 'STI Type' theta command to altitude error responses.

The dashed 'ignore altitude...' plots are there just for curiosity to see the effect of moving the pilots response to altitude block has on the frequency response.

$$\text{dashed plot} = \left(\frac{+P_{h\epsilon}}{-P_{\theta}} \right)$$

This ignores
 P_h block

$$\text{solid plot} = \frac{P_{h\epsilon}}{P_{\theta}} (G_2)$$

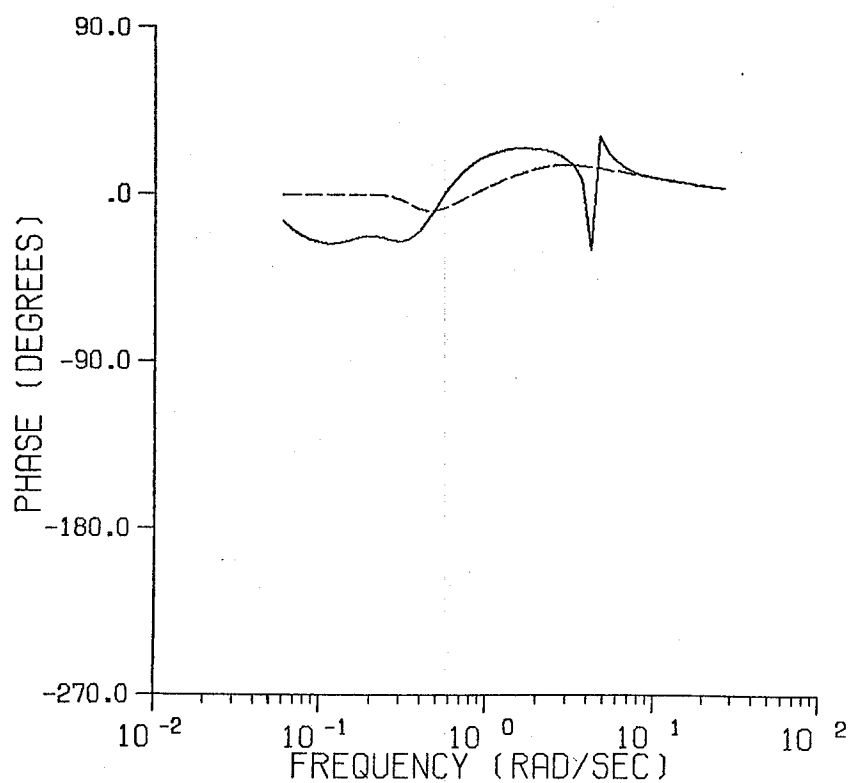
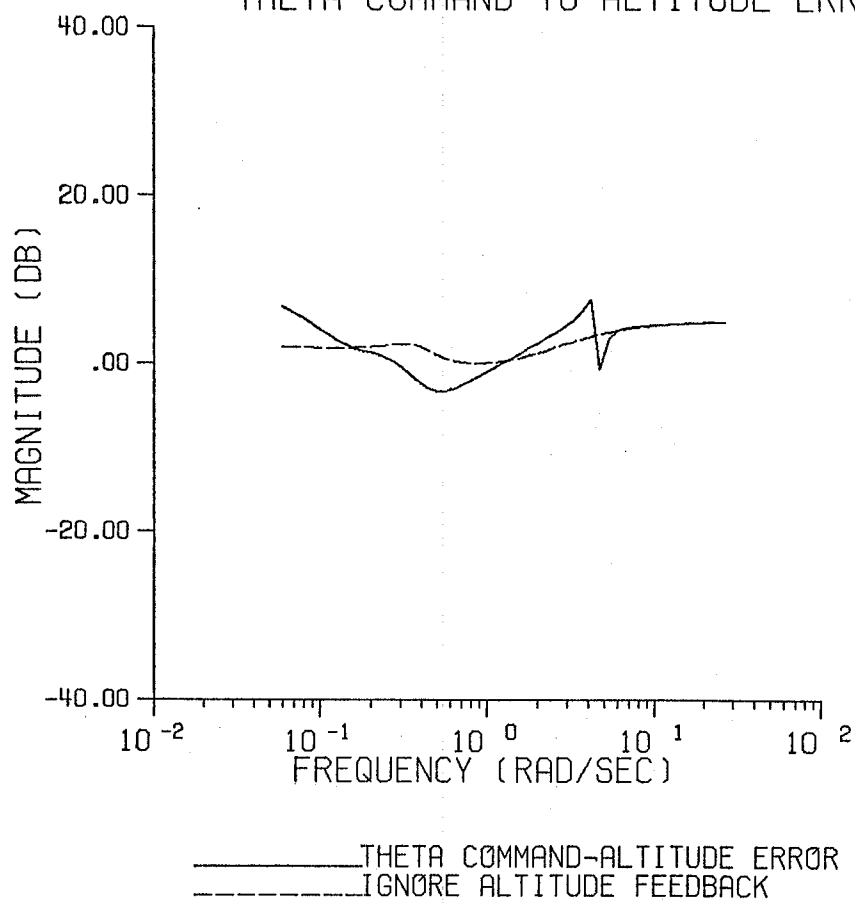
This includes P_h
block.

$$G_2 \triangleq \frac{H_{\theta}}{1 - \left(-\frac{P_h}{P_{\theta}} \right) H_{\theta} \left(\frac{h}{\theta} \right)}$$

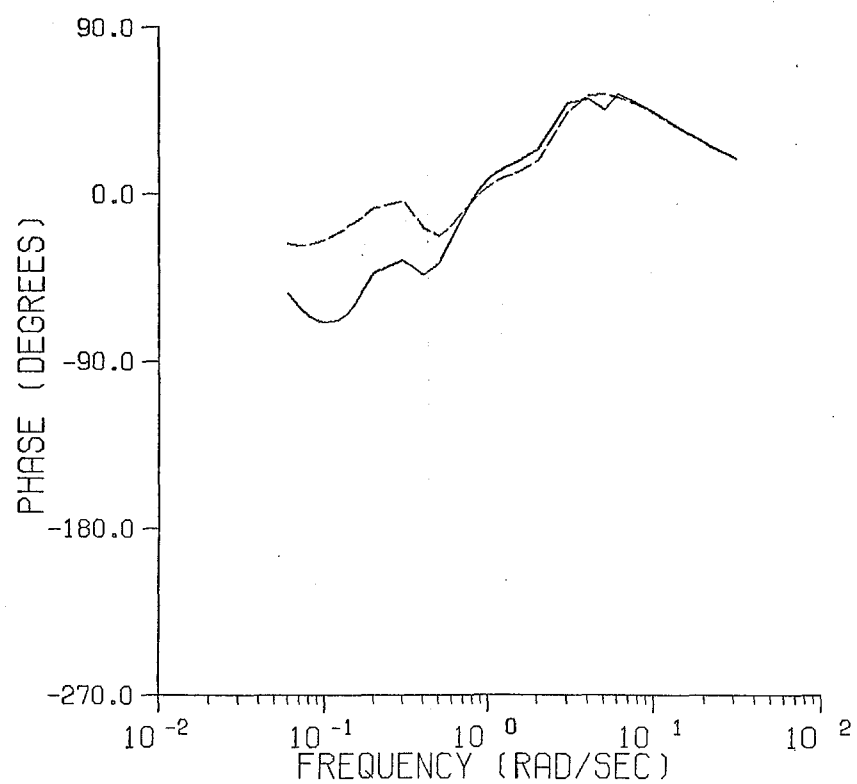
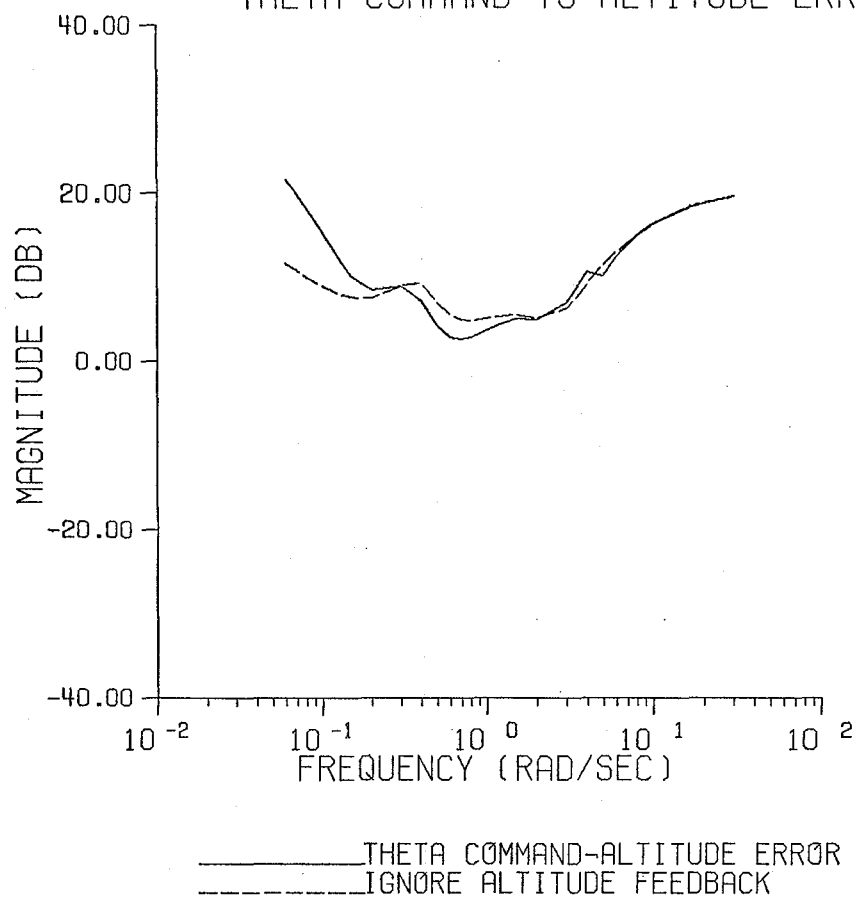
$$H_{\theta} \triangleq \left(-\frac{1}{P_{\theta}} \right) \left(\frac{-P_{\theta} \left(\frac{\theta}{\delta} \right)}{1 + \left(-P_{\theta} \right) \left(\frac{\theta}{\delta} \right)} \right)$$

CONFIGURATION 2-3 ALTITUDE TRACKING

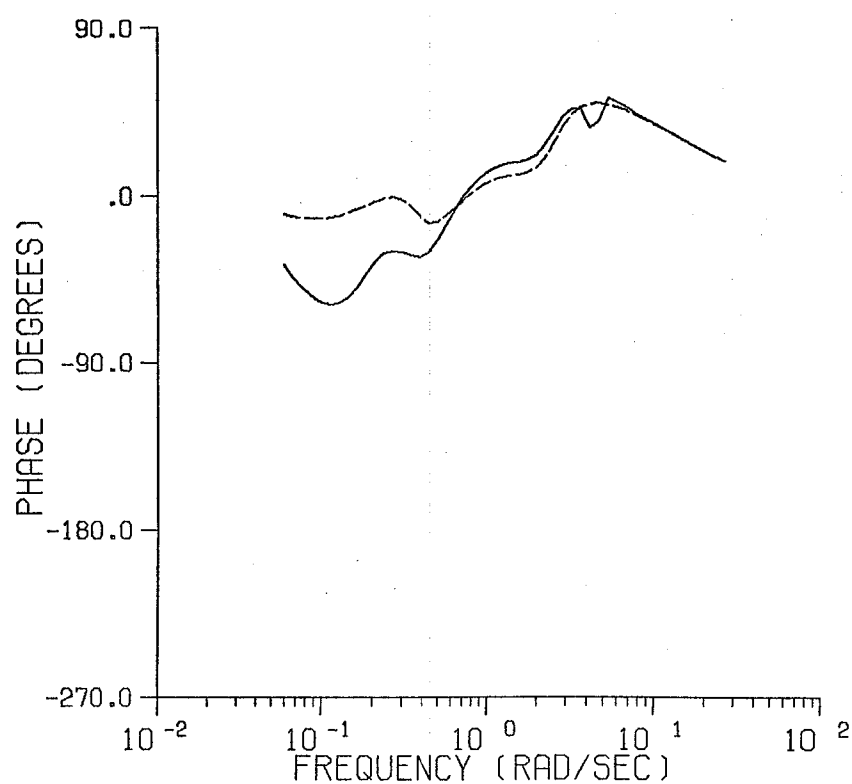
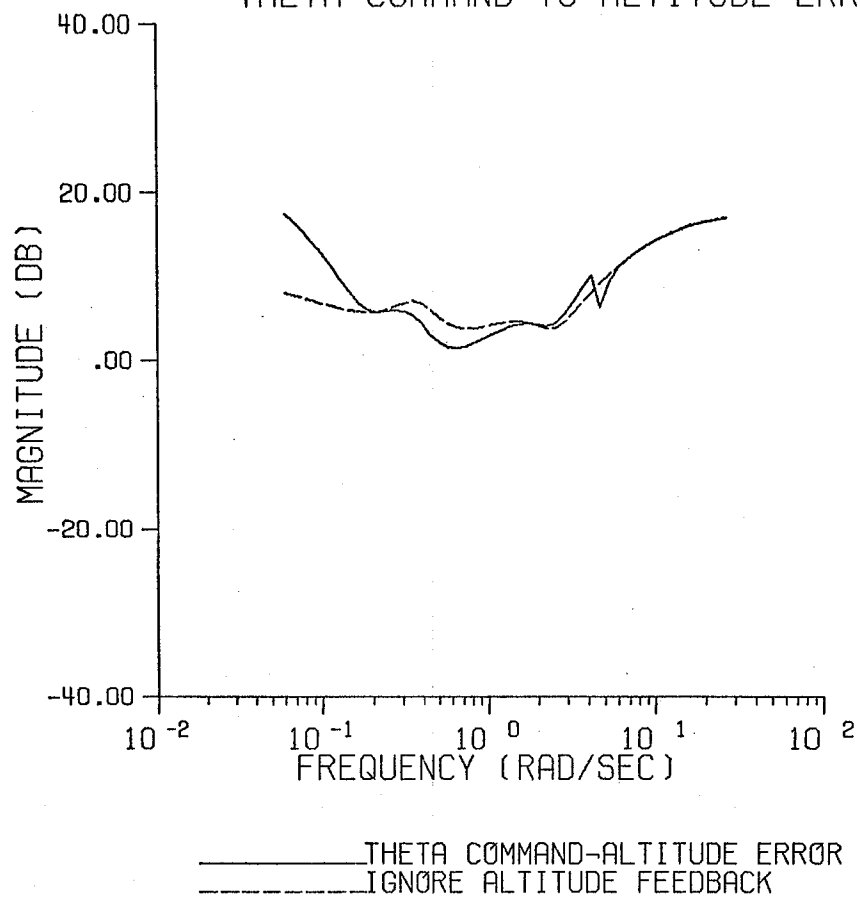
THETA COMMAND TO ALTITUDE ERROR



CONFIGURATION 3-1 ALTITUDE TRACKING
THETA COMMAND TO ALTITUDE ERROR

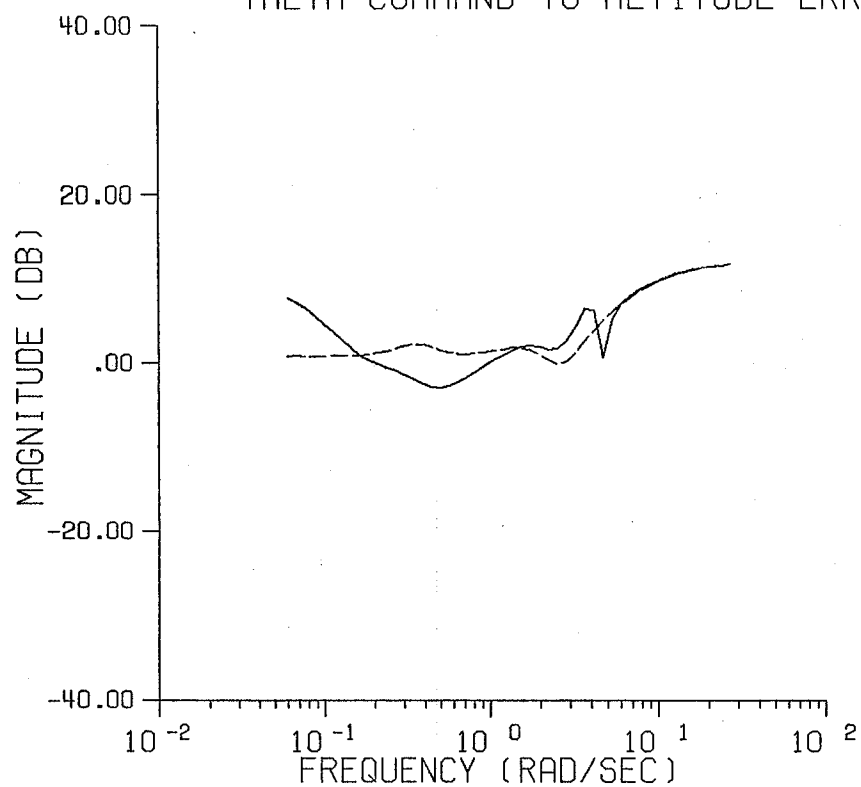


CONFIGURATION 3-2 ALTITUDE TRACKING
THETA COMMAND TO ALTITUDE ERROR

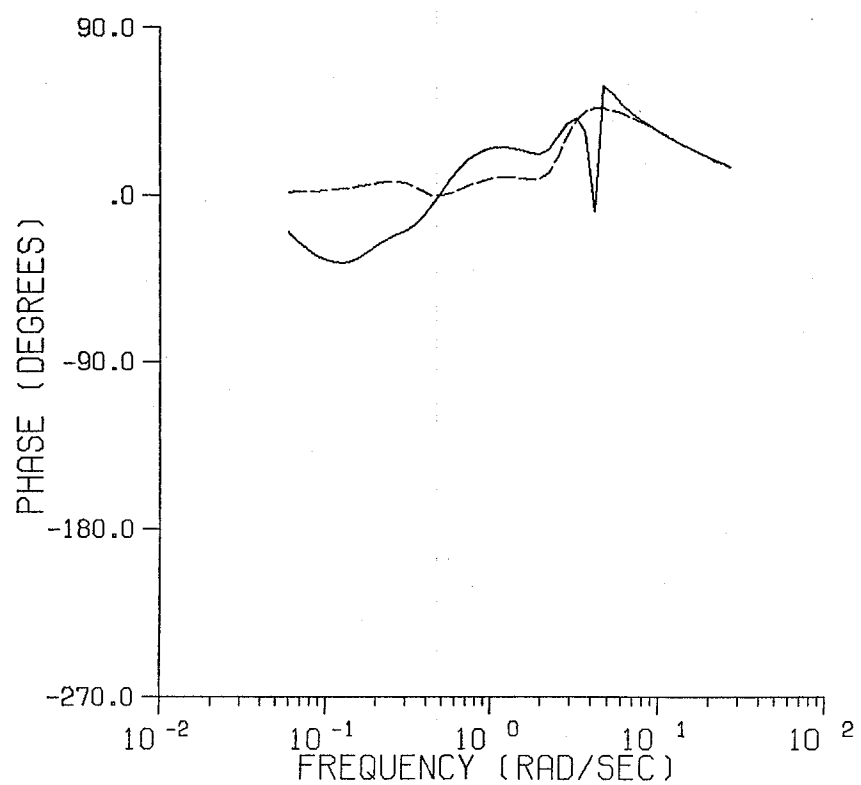


CONFIGURATION 3-3 ALTITUDE TRACKING

THETA COMMAND TO ALTITUDE ERROR

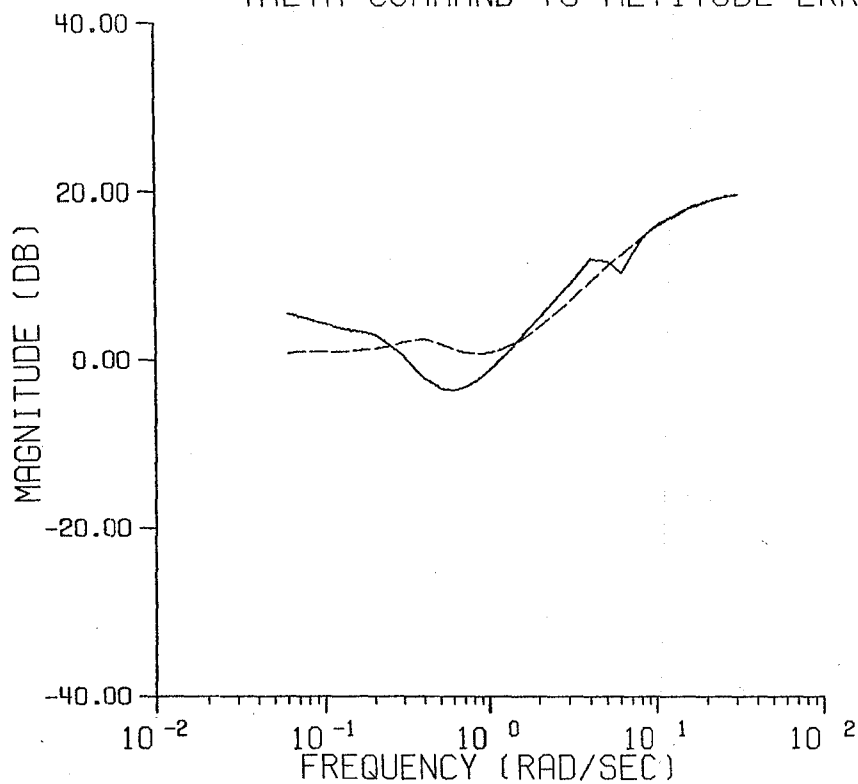


————— THETA COMMAND-ALTITUDE ERROR
----- IGNORE ALTITUDE FEEDBACK

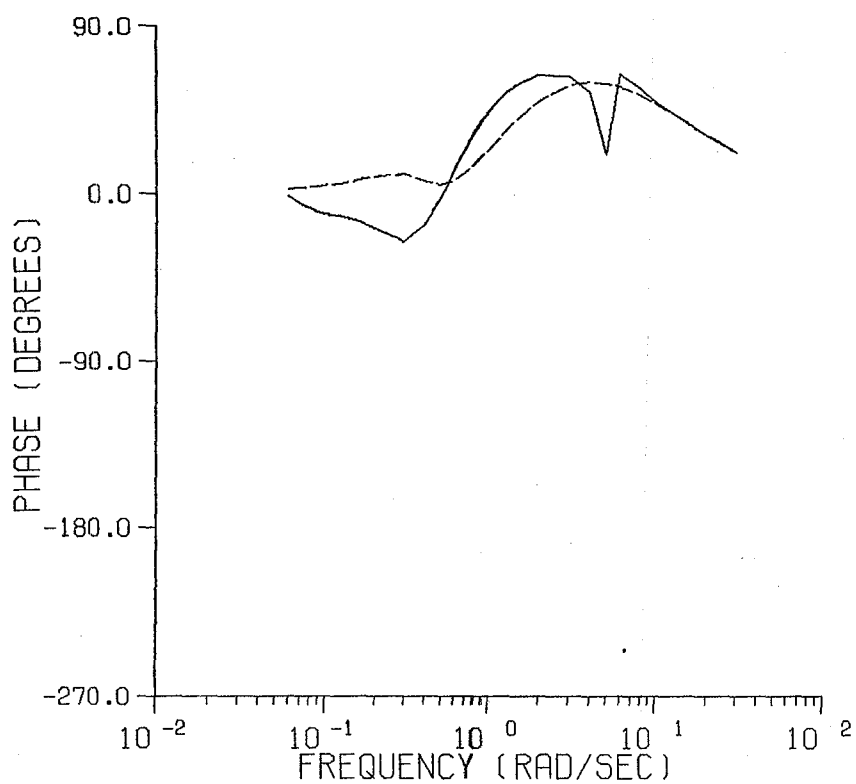


CONFIGURATION 4-1 ALTITUDE TRACKING

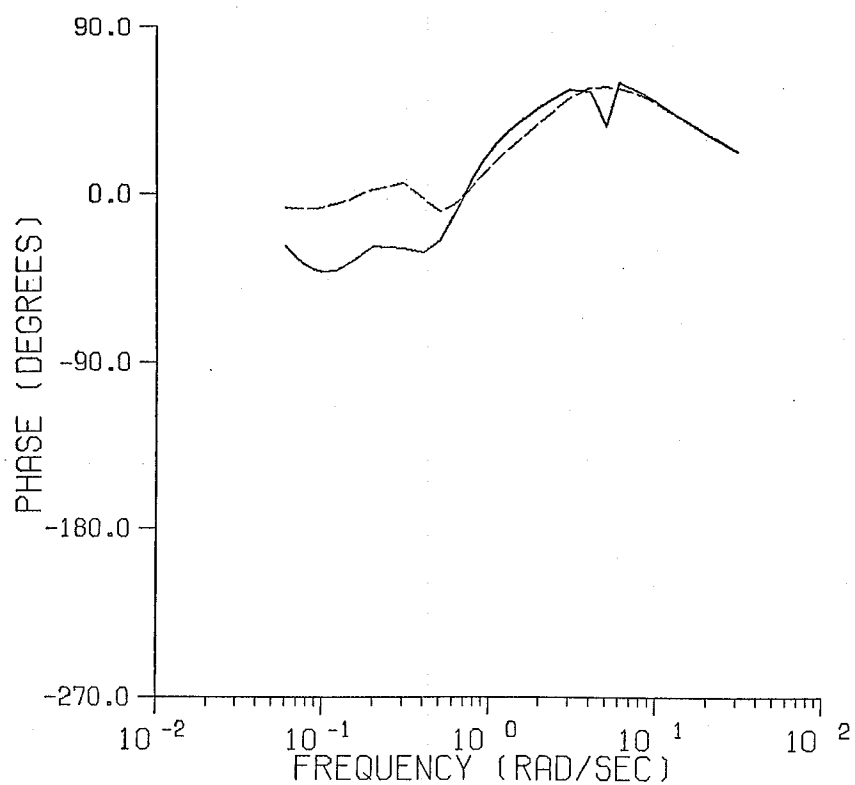
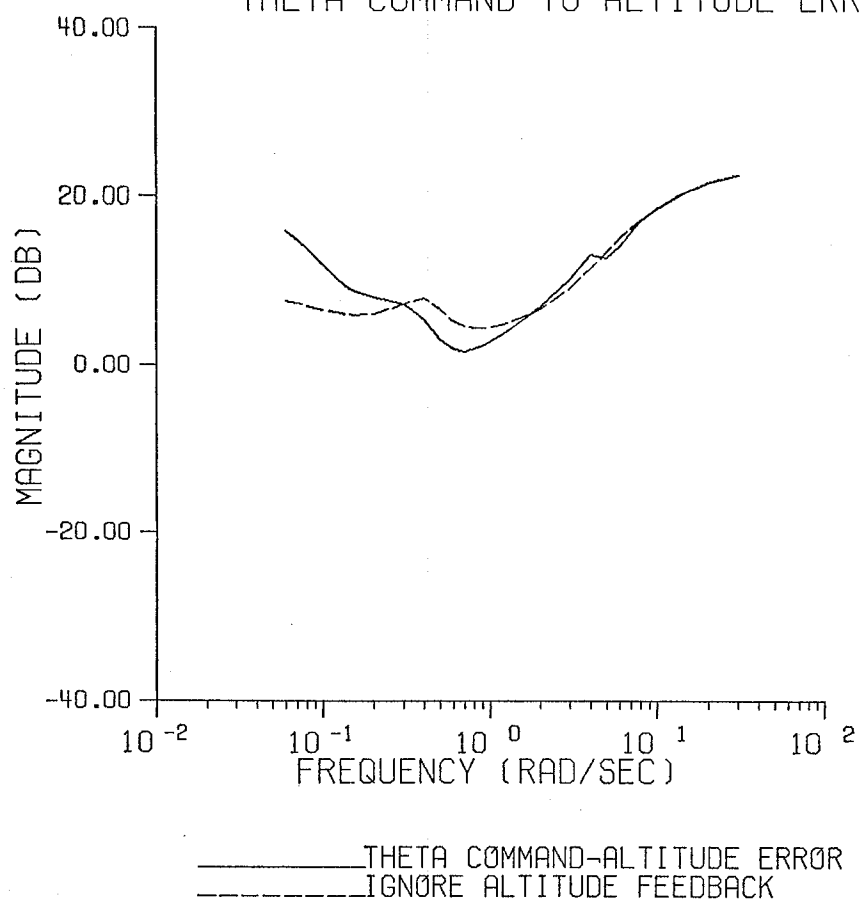
THETA COMMAND TO ALTITUDE ERROR



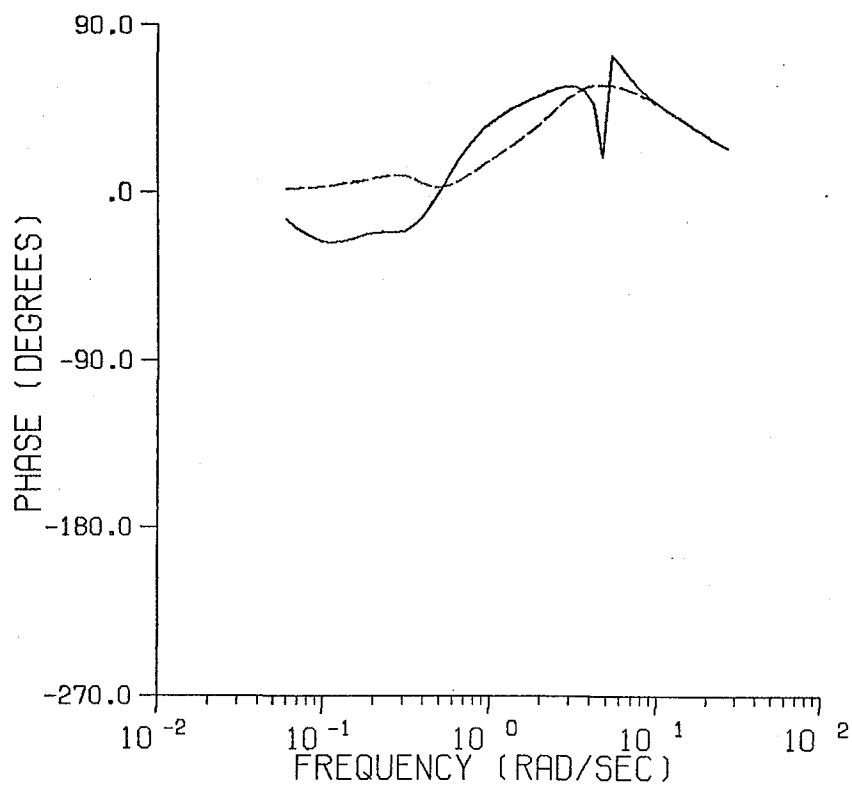
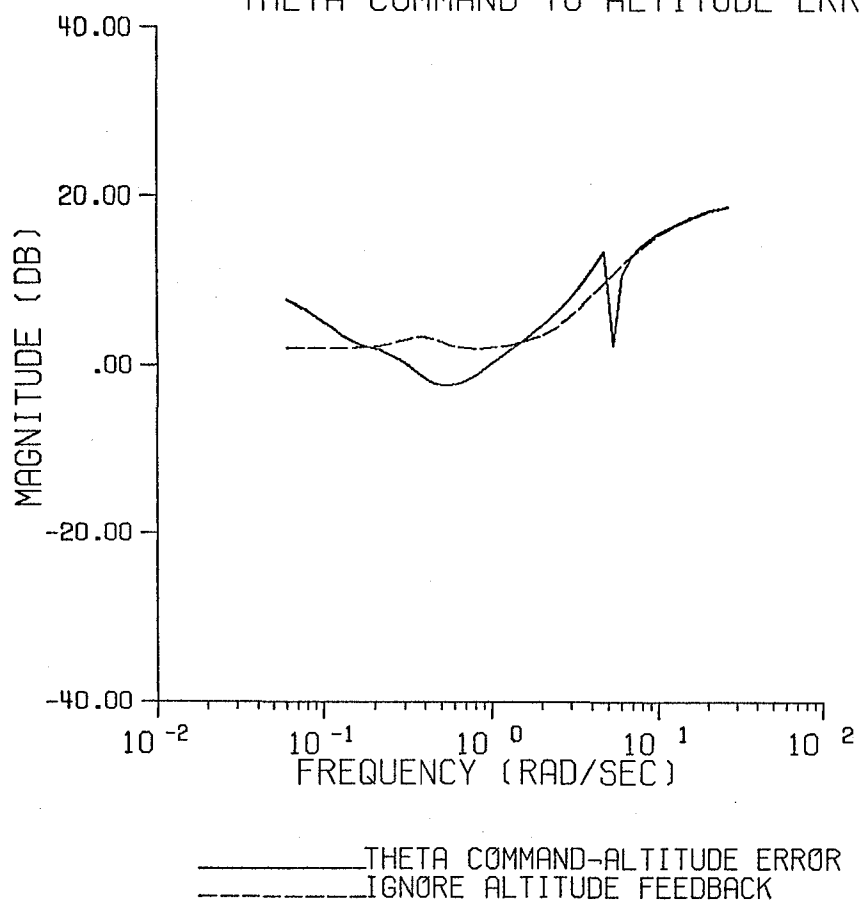
——— THETA COMMAND-ALTITUDE ERROR
----- IGNORE ALTITUDE FEEDBACK



CONFIGURATION 2-1 ALTITUDE TRACKING
THETA COMMAND TO ALTITUDE ERROR



CONFIGURATION 2-2 ALTITUDE TRACKING
THETA COMMAND TO ALTITUDE ERROR



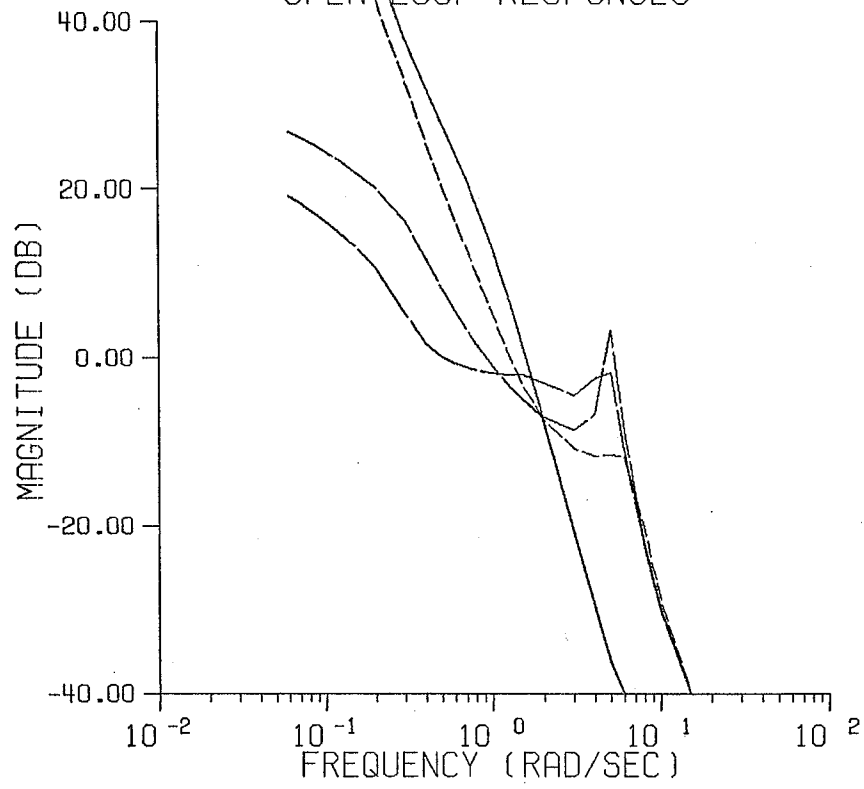
These plots are nearly worthless because of how 'complex' they are - but they show the effect of each pilot feedback on the open loop system response - (i.e. from the outer loop in).

{ '+ error compensation' means open loop aircraft h/δ with the $P_{h\epsilon}$ block in cascade.

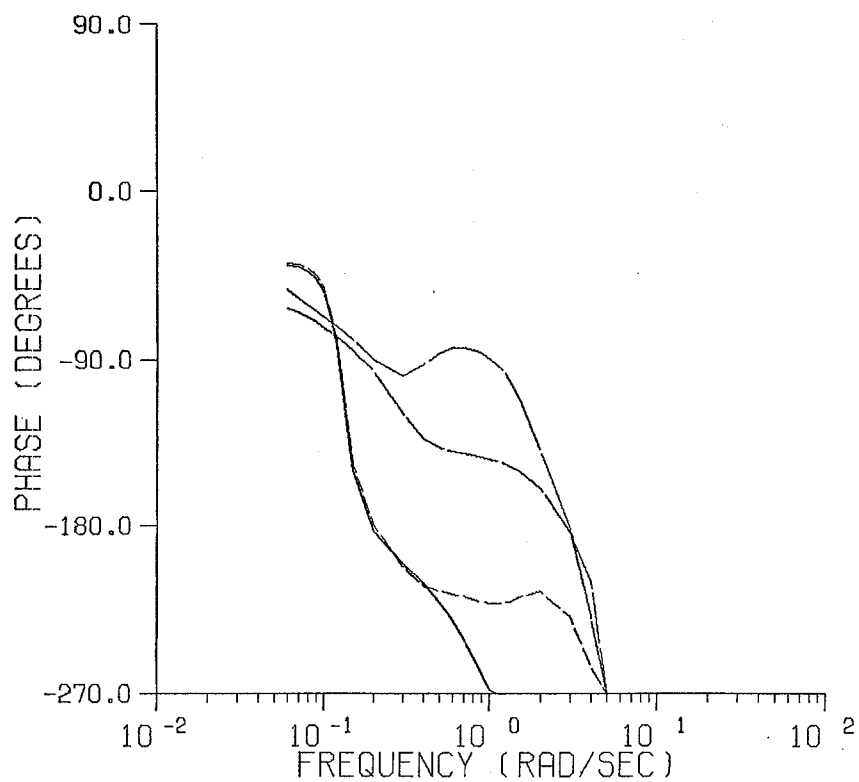
{ '+ error + theta' means above with the inner theta pilot feedback loop closed.

{ '+ error + θ + altitude' means above with additionally the pilots altitude feedback loop closed.

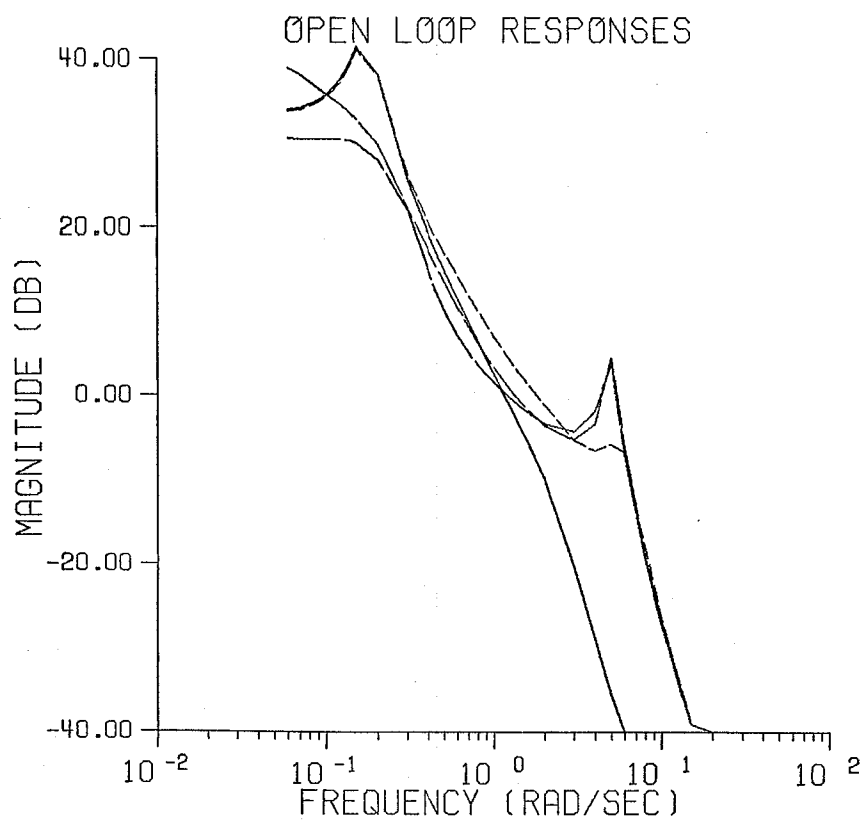
CONFIGURATION 1-1 ALTITUDE TRACKING
OPEN LOOP RESPONSES



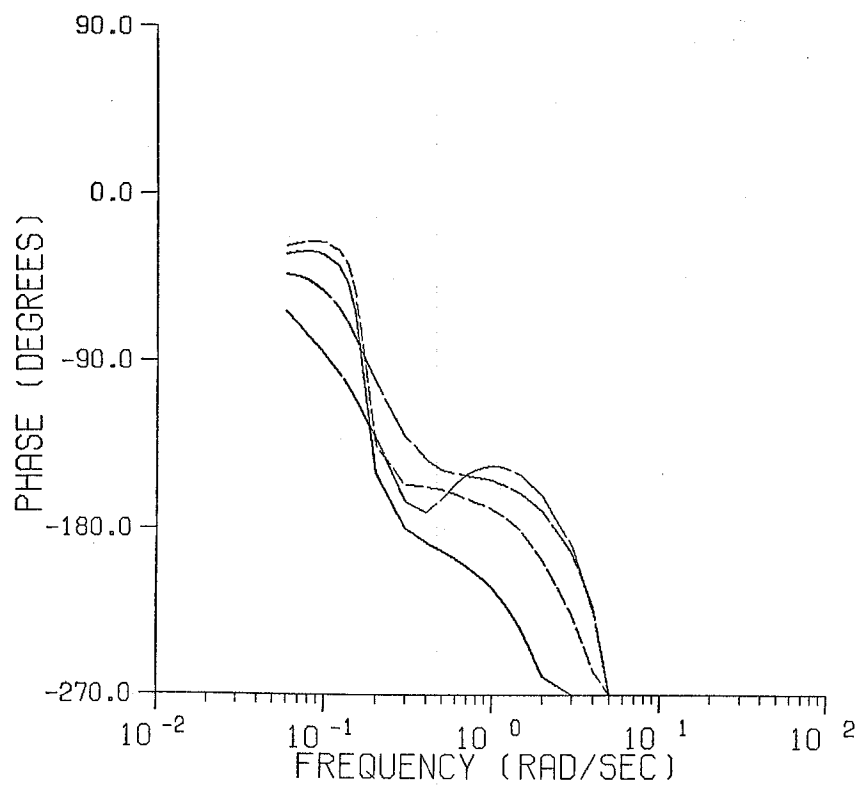
— AIRCRAFT ALTITUDE RESPONSE
- - - +ERROR COMPENSATION
— +ERROR + THETA
— +ERROR+THETA+ALTITUDE



CONFIGURATION 2-1 ALTITUDE TRACKING

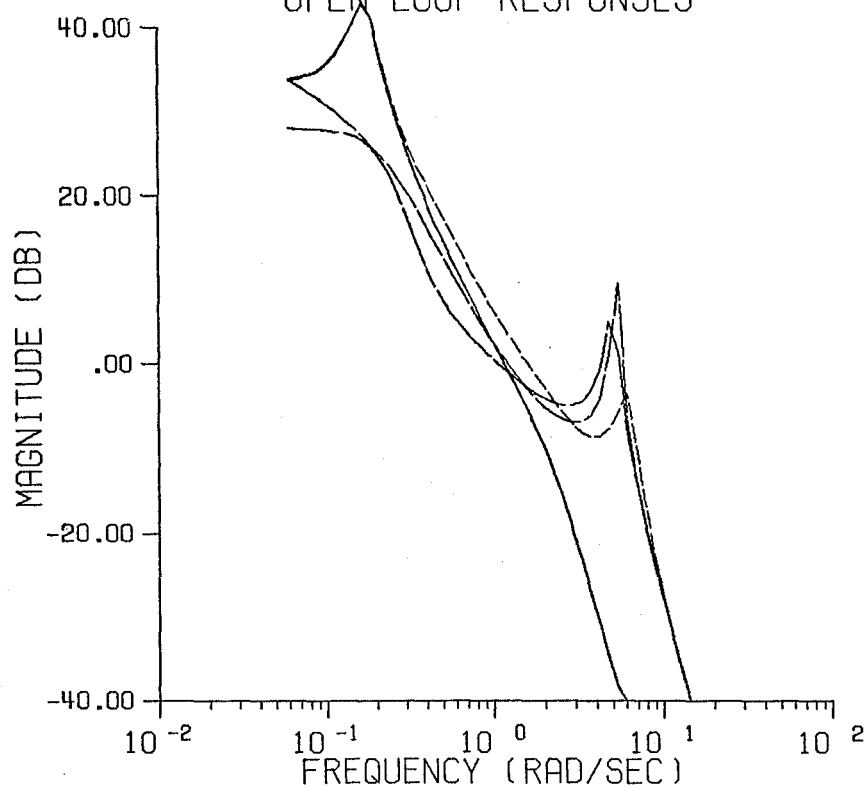


—— AIRCRAFT ALTITUDE RESPONSE
- - - - +ERROR COMPENSATION
—— +ERROR + THETA
- - - - +ERROR+THETA+ALTITUDE

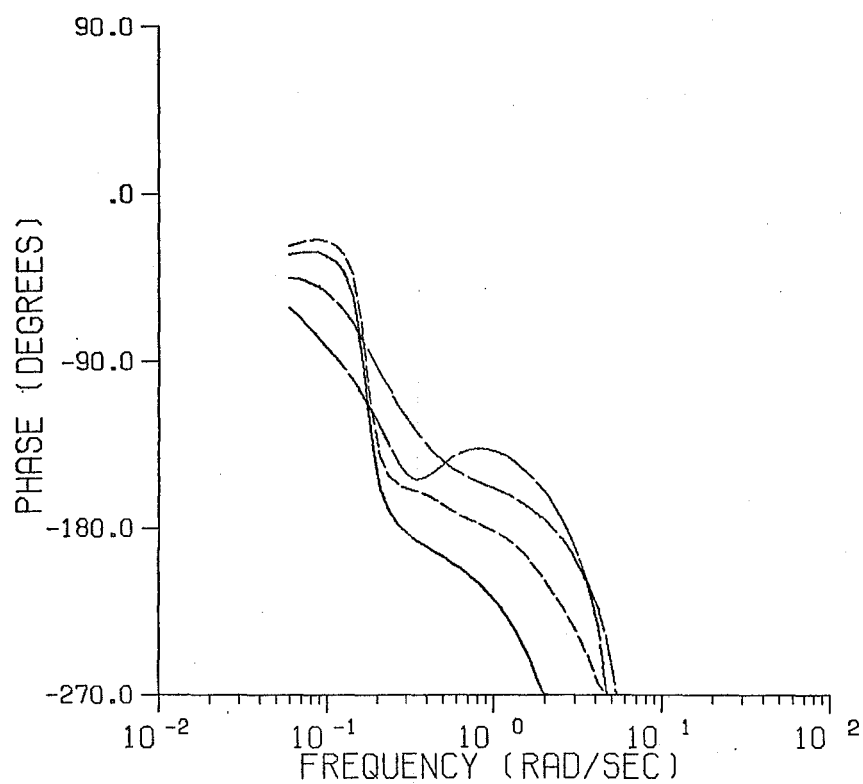


CONFIGURATION 2-2 ALTITUDE TRACKING

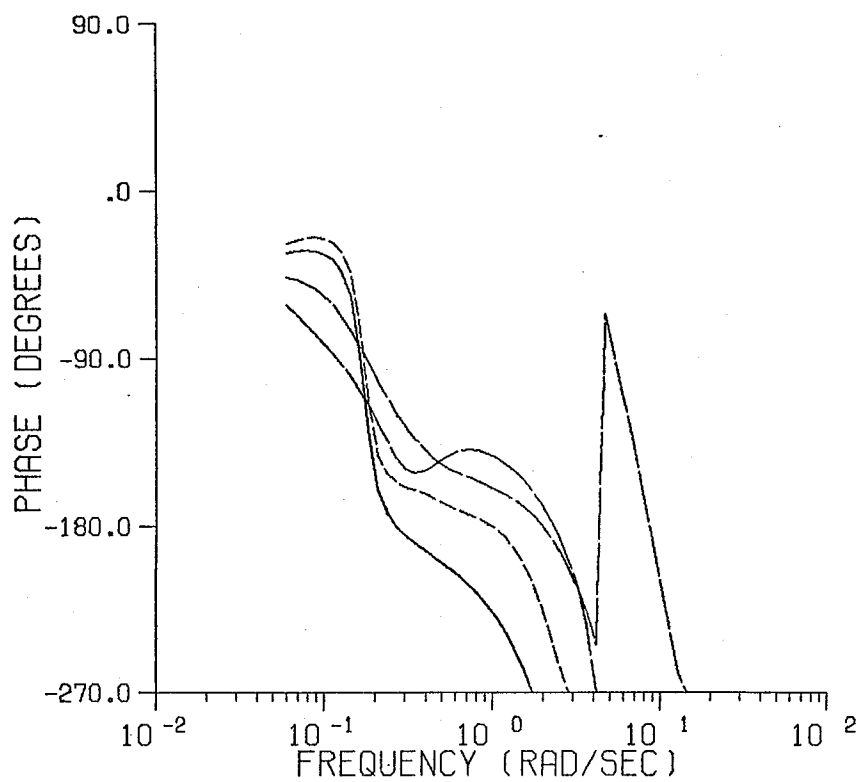
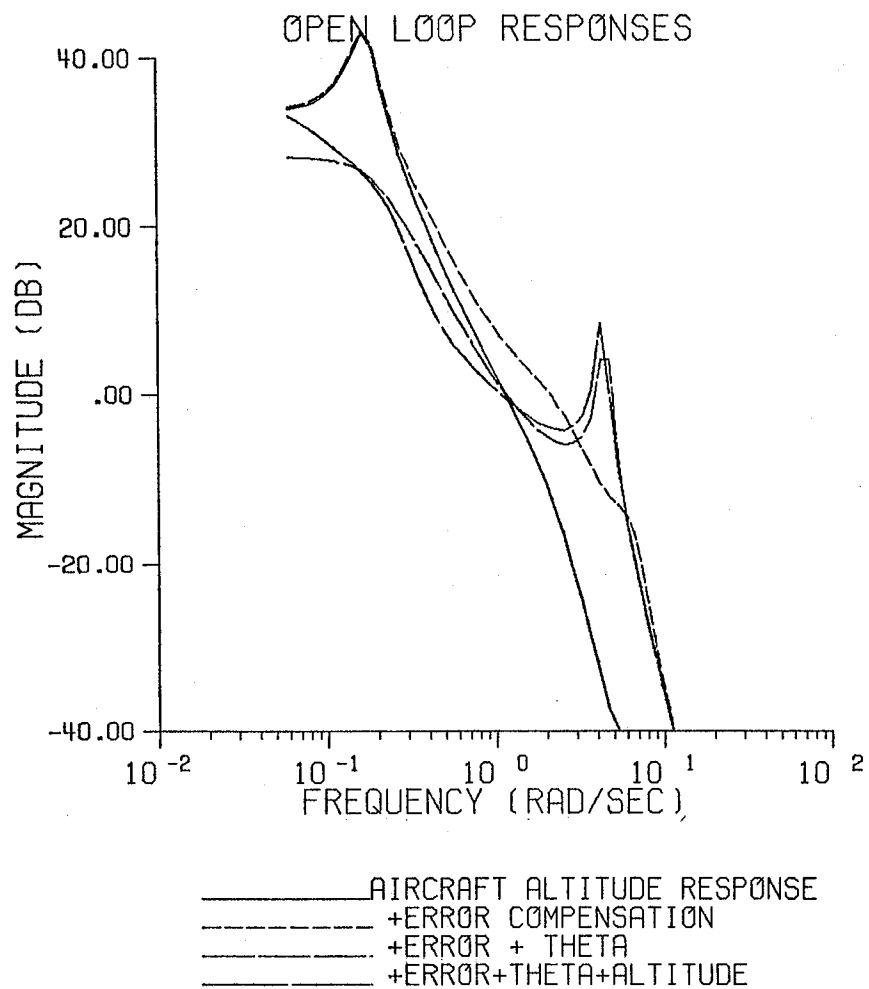
OPEN LOOP RESPONSES



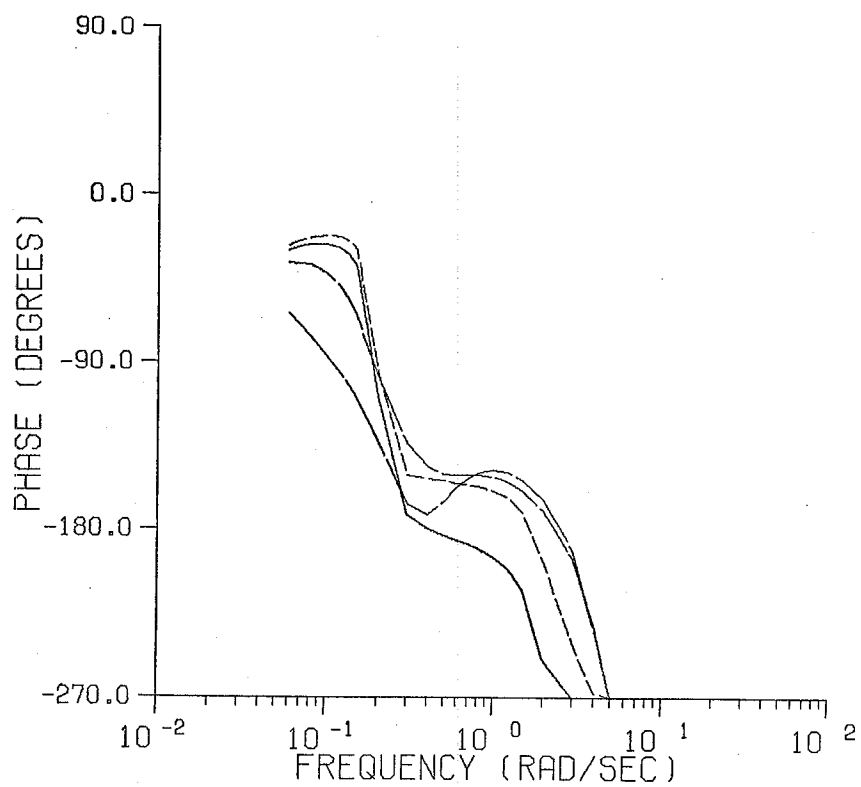
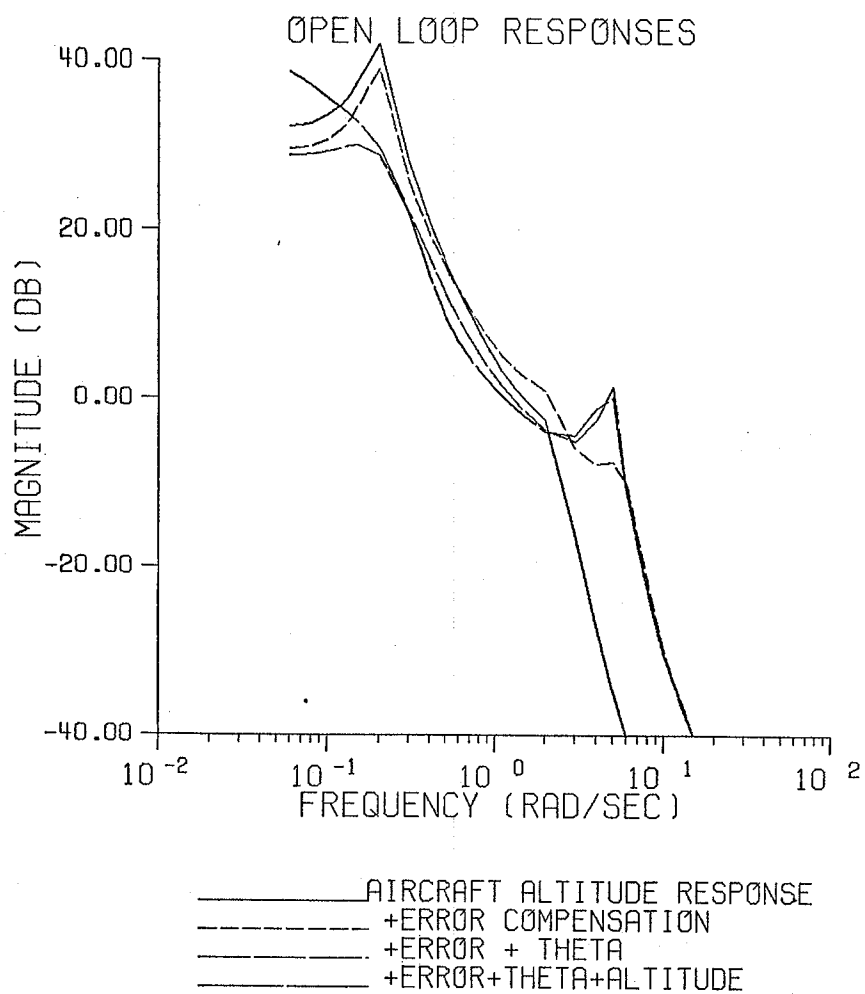
—— AIRCRAFT ALTITUDE RESPONSE
- - - +ERROR COMPENSATION
—— +ERROR + THETA
—— +ERROR+THETA+ALTITUDE



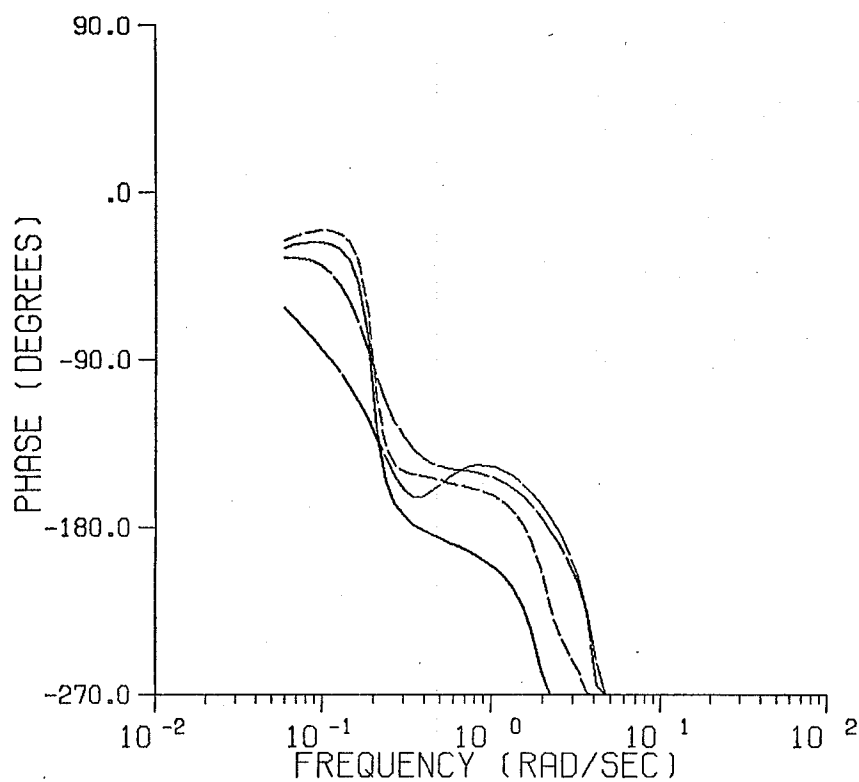
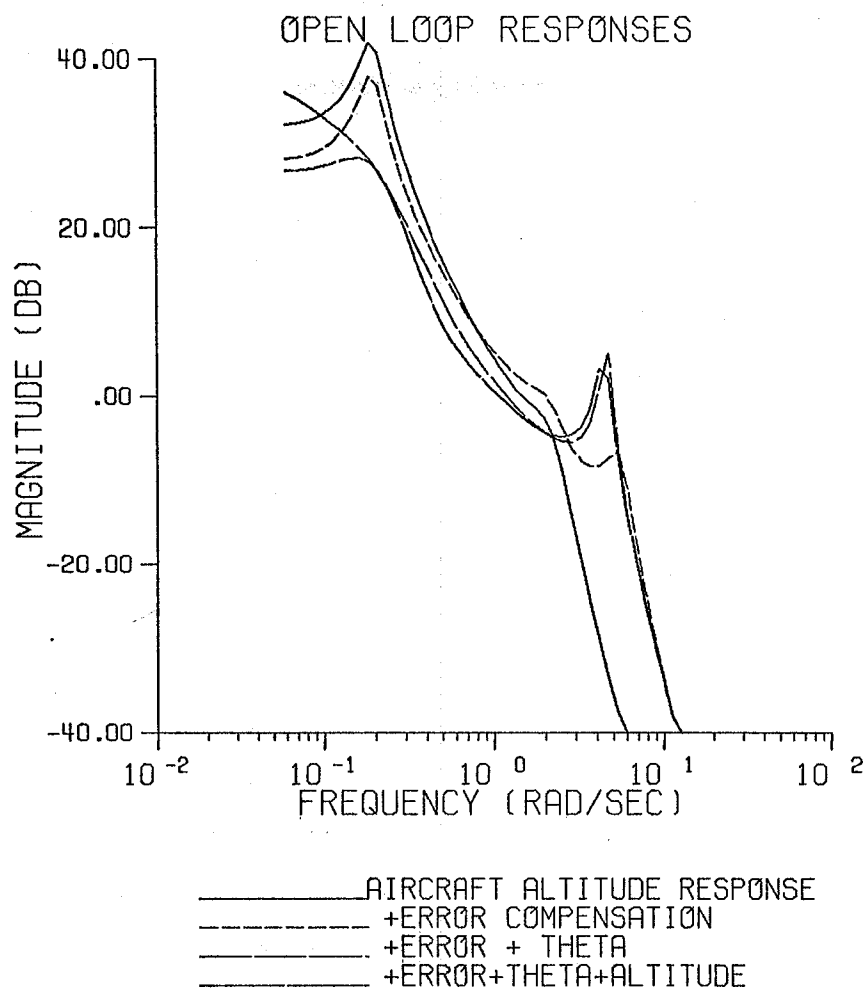
CONFIGURATION 2-3 ALTITUDE TRACKING



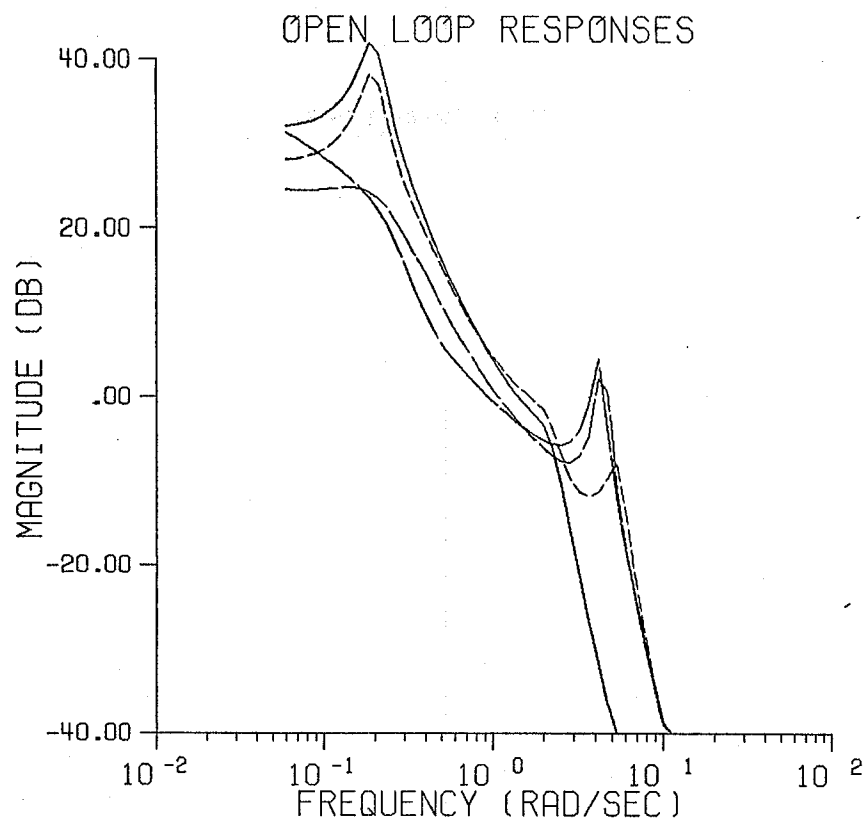
CONFIGURATION 3-1 ALTITUDE TRACKING



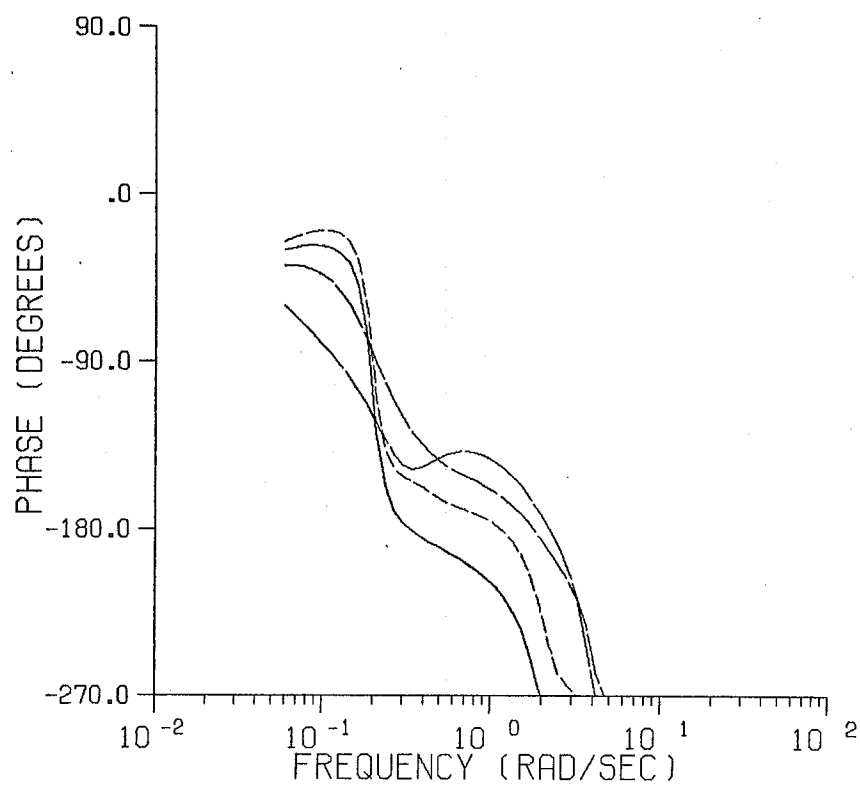
CONFIGURATION 3-2 ALTITUDE TRACKING



CONFIGURATION 3-3 ALTITUDE TRACKING

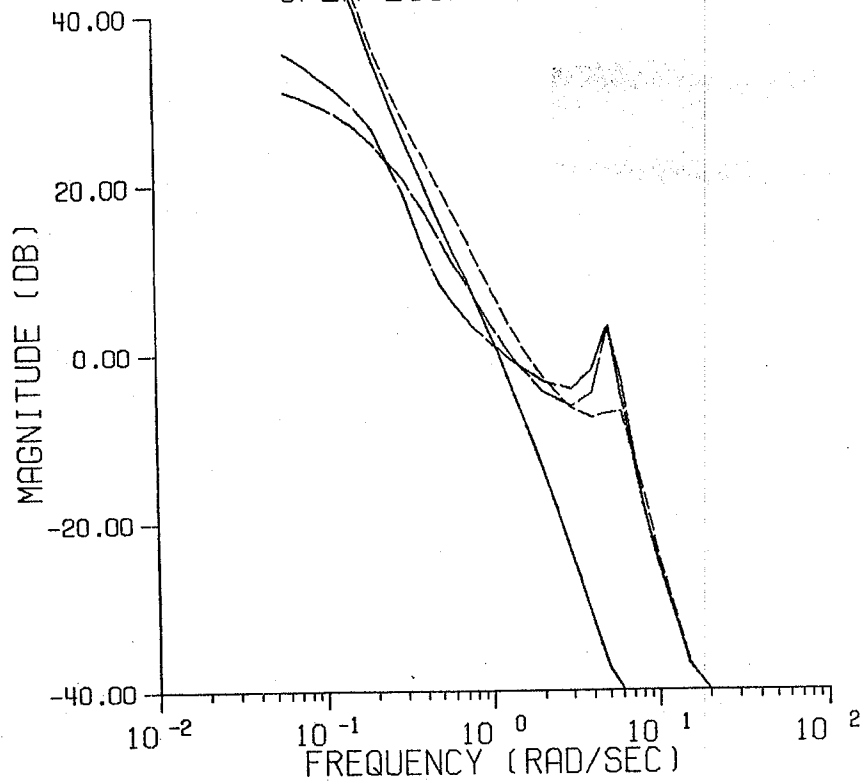


— AIRCRAFT ALTITUDE RESPONSE
- - - +ERROR COMPENSATION
- - - +ERROR + THETA
- . - +ERROR+THETA+ALTITUDE

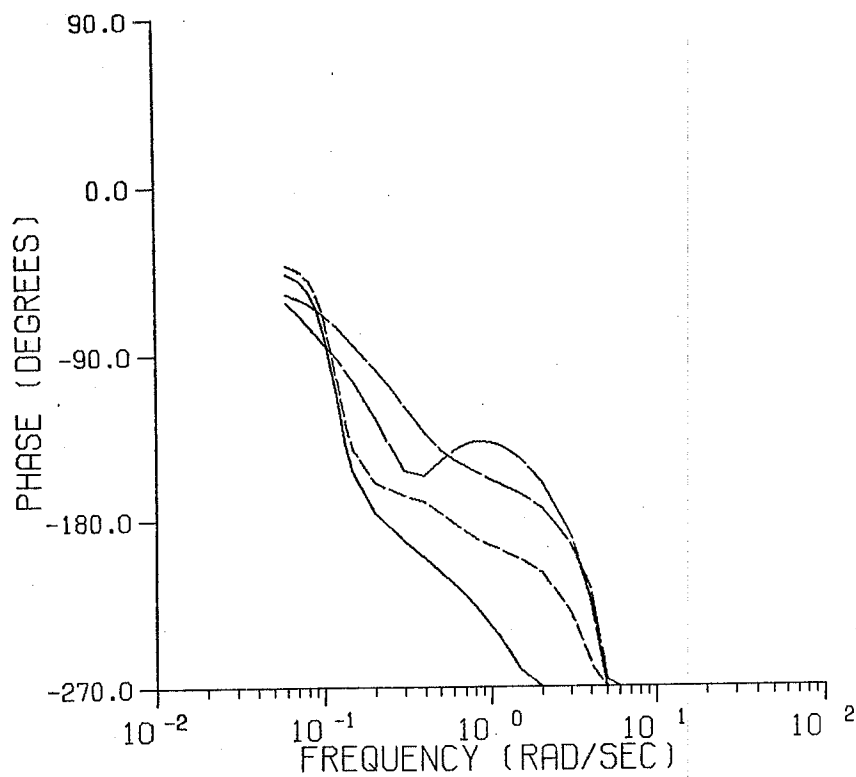


CONFIGURATION 4-1 ALTITUDE TRACKING

OPEN LOOP RESPONSES



—— AIRCRAFT ALTITUDE RESPONSE
- - - - +ERROR COMPENSATION
—— +ERROR + THETA
—— +ERROR+THETA+ALTITUDE



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